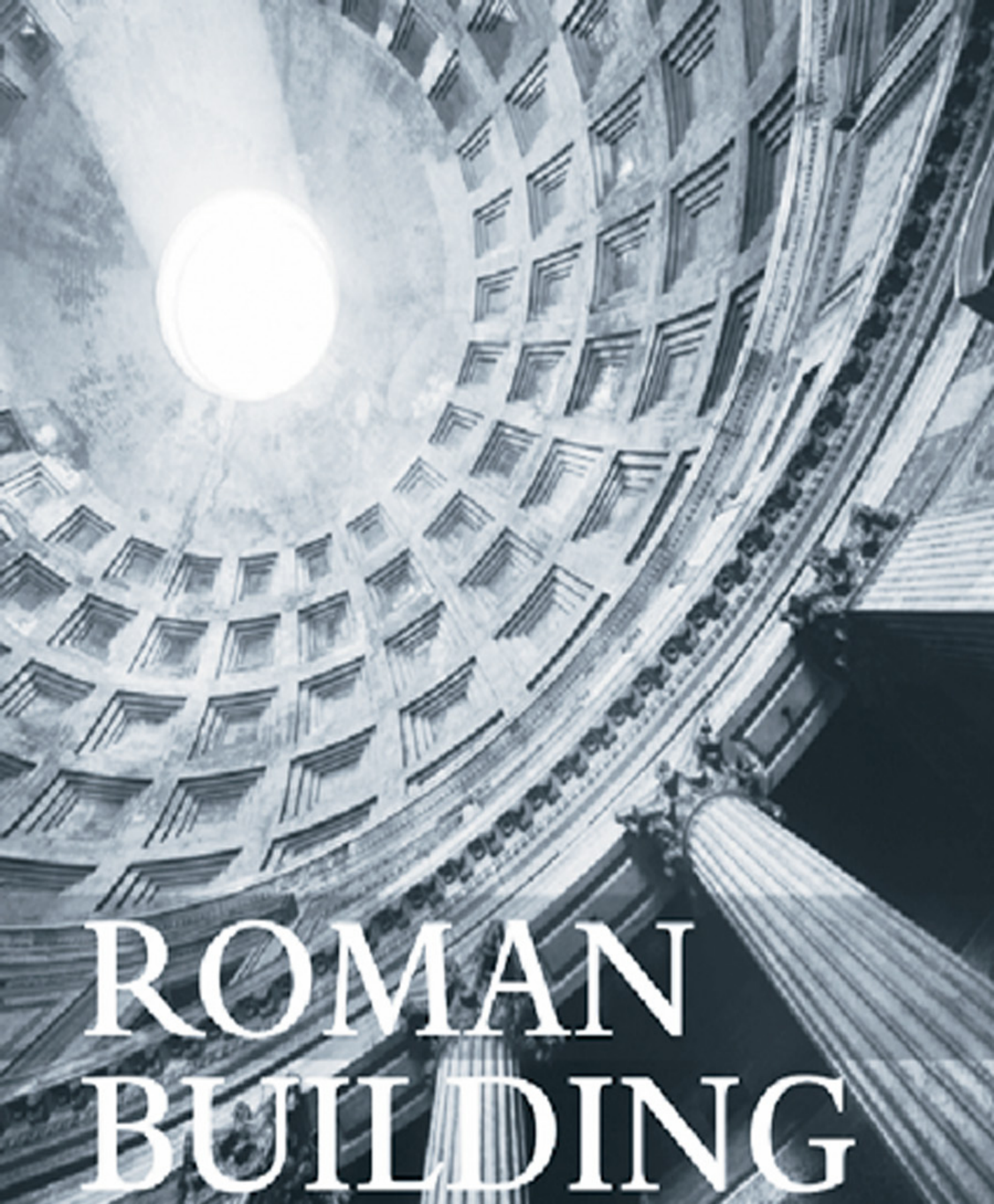


ROMAN BUILDING

Materials and Techniques

Jean – Pierre Adam

ROMAN BUILDING

Materials and Techniques

ROMAN BUILDING

Materials and Techniques

Jean-Pierre Adam

Translated by Anthony Mathews

London and New York

Routledge is an imprint of the Taylor & Francis Group
This edition published in the Taylor & Francis e-Library, 2005.

"To purchase your own copy of this or any of Taylor & Francis
or Routledge's collection of thousands of eBooks please go to
http://www.ebookstore.tandf.co.uk/."

Published in French as *La Construction Romaine: matériaux et techniques*

First published in English 1994 by B.T.Batsford Ltd

First published in paperback 1999 by Routledge 11 New Fetter Lane, London EC4P 4EE

British Library Cataloguing in Publication Data A catalogue record for this book is available from the British Library

ISBN 0-203-98436-6 Master e-book ISBN

ISBN 0-415-20866-1 (Print Edition)

CONTENTS

FOREWORD

Of all the kinds of architecture that have appeared and developed in the course of the last five millennia, Roman architecture is extraordinarily rich in terms of the buildings, monuments and structures which survive, and the variety of materials and means by which they were constructed. Much of our respect for Roman architectural achievement can be attributed both to this remarkable survival and to the incorporation of Roman theoretical and practical ideas into the practice of architecture from the Renaissance to the present day. In these circumstances it is surprising that there has been no modern study of Roman constructional and building techniques and it is this gap which Jean-Pierre Adam's book sets out to fill. It aims to provide a systematic study of building materials and the various types of building technique, in brick, stone and marble; arch and vault construction; carpentry; types and techniques of interior decoration; and methods of civil engineering for water supply, heating, baths and roads. Minor domestic buildings, workshops and shops are also considered.

The closeness of the relationship between the past and the present alluded to above is, to a great extent, due to two outstanding and complementary names, which, between them, unite theory and practice. They are Vitruvius and Pompeii, both of which have served as a major source of inspiration in the preparation of this book. Vitruvius is the most important writer on Roman architectural theory and practice whose work, *The Ten Books of Architecture,* survives in its entirety. The subject matter of his influential survey ranges through architectural principles, the origin of building and the use of materials, the study of individual types of building such as temples, theatres, baths, harbours and town and country houses, and also includes a range of technical and engineering themes. Vitruvius' work was clearly regarded as important by successive generations of Roman architects, but it is still unclear how far his precepts actually reflected contemporary practice or were put into action within the Roman world in general. Certainly his writings are frequently turned to by modern scholars in their attempts to understand ancient structures, and to see how far they measure up to the principles laid down by Vitruvius. The latter would be easier to interpret if illustrations survived as well as the text; thus ample provision of photographs and line drawings is a key feature of Adam's book.

Illustration is where Pompeii plays a vital role as an exemplar of Roman practice. The destruction of the community in AD 79 and its burial in volcanic ash has ensured the survival of the town with a representative range of types of buildings and construction techniques current in the first century AD. Indeed it provides examples of buildings and other structures which span a period both before and after the life of Vitruvius. The main focus of research at Pompeii has been on the city plan, but not on the techniques of construction and the ideas and issues which influenced their choice. Pompeii offers an outstandingly good starting point and it has been one of the principal sources for this research. However, it has to be remembered that Roman buildings and monuments are visible all around the Mediterranean. For this study Jean-Pierre Adam has turned to sites other than Pompeii to provide examples of major imperial buildings, as well as those which employed marble and stone-block construction; all being aspects of Roman building poorly represented at Pompeii.

Jean-Pierre Adam acknowledges a great debt of gratitude to earlier scholars in this field. In particular he would like to single out A.Choisy, Giuseppe Lugli, Luigi Crema and J.B.Ward-Perkins, who, between them, have drawn attention to the most representative Roman monuments for studying techniques of construction. Finally, it is also appropriate to acknowledge the influence of the great student of Greek architecture, the late A.Orlandos. Considerable assistance on technical matters has been given by living craftsmen in France and Italy and elsewhere around the Mediterranean; a further illustration of the survival of long-established practices to the present day.

The selection, definition and etymology of technical terms are derived from different works or oral sources and are cited in the bibliography, rather than continually throughout the text. Photographs and line drawings have been chosen in order to provide a representative rather than definitive range. As far as possible the illustrations draw on actual examples, but where the remains are insufficient to be informative, Jean-Pierre Adam has relied on his own reconstructions, indicating any important details. Unless otherwise acknowledged in the captions, all line illustrations and photographs are by Jean-Pierre Adam.

It is a tribute to the interest already aroused by Jean-Pierre Adam's work that, even in the short time which has elapsed since its original publication in 1989, new research is continuing to advance rapidly our understanding of Roman buildings, the materials and techniques of their construction. Studies of the exploitation, characterisation and use of Roman marble, in particular, have been prolific in the intervening years. Progress in individual areas such as marble studies serves only to enhance the value of an original overview such as this, which seeks to bring together the many disparate elements that make up the overarching theme of this book.

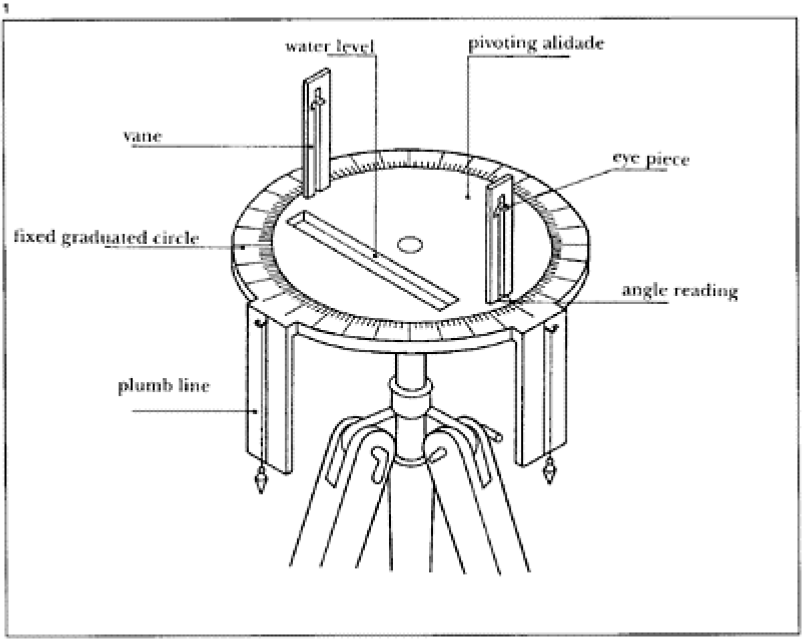
In the collection and organization of the documentary material, this book would not have been possible without the constant help and support of Thérèse Adam, the author's wife, who, after many journeys around the Mediterranean, apparently became a remarkably competent *agrimensor*.

Michael Fulford
University of Reading
January 1993

1
SURVEYING

Wherever architecture and public works and rural and urban planning appear to be the result of systematic techniques,[1] surveying has been a necessary precondition. An indispensable step between the architect's plan and its realization, surveying holds the same intermediate position in the converse operation: that is, in the reconstruction of the plans of a monument or of a natural area, based on what survives. Three operations define the discipline of surveying and determine the methods and instruments used: the establishment of bearings, the measurement of distances and the estimation of heights.

While the Egyptian geometer is known to us both through administrative and funerary texts and through



1 Proposed reconstruction of the *dioptra* for carrying out horizontal angular measurements.

visual representations,[2] his Greek counterpart is familiar only through literature, the opposite of the Roman case for which, once again, sources abound.[3]

Even though we have no direct visual knowledge of the Greek geometers, through either depictions or actual objects, their high technical level is displayed, as is the potential precision of their instruments, by certain finds relating to parallel activities. An example of this is the Antikythera mechanism[4] and its remarkable mechanical construction.

The essentials of surveying are described by Hero of Alexandria,[5] who mentions in particular the complex problems of land surveying, such as the boring of a tunnel from both ends or the calculation of the distance between two remote points. Elementary operations such as alignment were not considered by him to be a problem or to be impossible to perfect.

To perform the measurements quoted in his treatise, Hero describes the use of angle-measuring tools, such as the *dioptra*.[6] There are no surviving examples or representations of this and so it can only be shown in the form of a drawn reconstruction (fig. 1). Hero proposed some improvements to the basic form of this apparatus, allowing it to be used in astronomy: he added a gear mechanism and a second vertical disc, transforming it into a theodolite minus a lens. It is not known whether the Greeks thought of applying the principle of the *dioptra,*[7] consisting of a rule with a sight reference or vane at each end, to plotting directly on to parchment. Hero makes no mention of it but, since his purpose was to apply mathematical research to surveying and astronomy, his notes are only concerned with angle measurement.

For the simplest operations the equipment of the ancient surveyor hardly differed from that which remained in use in rural areas until the beginning of the twentieth century: the graduated rule or *Κανώυ* (canon), whose name has come to be applied to a level of academic standard, which is found used as both an instrument and a unit of measurement—the rod and the perch; the cord or *σταθμη* used for alignment or as a measure (it is the origin of the surveyor's old land measurement, the chain); the cross head, *χύνωμωυ,* cited by Aristophanes as a precise instrument used to excess by Meton;[8] and the cord with two pegs, the *τόρνος,* for marking circles and arcs of circles on the ground.[9]

Finally, when considering the great achievements of the Romans, especially in the field of water supply, it must be remembered that, though they built on the research of the Greeks with a remarkable efficiency, the latter show no less evidence of some spectacular attainments, for example the channelling of water at Pergamon across particularly difficult terrain,[10] or the tunnel of Samos which was bored from the two ends, using the plans of Eupalinos.[11]

The Roman *agrimensor* is known mainly for the technical works his profession has left behind, including the fragments recovered from the surveying treatise of Frontinus. These texts, gathered in a collection entitled *Gromatici veteres,*[12] give precise information on the practical methods of the profession and the framework in which it evolved. However, for the interpretation of the written evidence, we can turn to the writings of experts whose analyses are an indispensable complement, even a precondition, to the attempt to achieve a proper understanding.[13]

Fortunately, the surviving Roman archaeological material complements this theoretical expertise, as is still visible in the surviving constructions, and both elements are brought together in the following short practical study.[14] Two surveying tools will be used in the experiment: the *groma*[15] and the *chorobates*. The functions of these tools are complementary and are at the heart of standard surveying techniques used in the location of a building, a road or an aqueduct. In order to demonstrate the technical possibilities open to the *agrimensor,* whose range of techniques would be familiar to a modern surveyor, the experiment will be extended also to an exercise in land levelling, which is also part of the operations of land registry.[16]

In order to understand better the use of both the *groma* and the *chorobates,* it is necessary to remind ourselves of the nature of surveying work.[17] Alignment is the first and the most common of the operations; as the term indicates it facilitates the laying out of axes and boundaries, essential to all construction and public building works. Alignment, by the use of cords over short distances, or marker poles over longer ones, presents difficulties only on uneven ground; on a slope, the surveyor takes a series of inclined sightings, keeping the poles in the same vertical alignment. In addition the alignment has to be accompanied by measurement of the distance covered, and the method used is a series of stepped, horizontal sightings and measurements. Step-levelling was known to the *agrimensor* under the name of *cultellatio*[18]: the word has remained in French usage (though rare in English) as *cultellation* or *cutellation*.

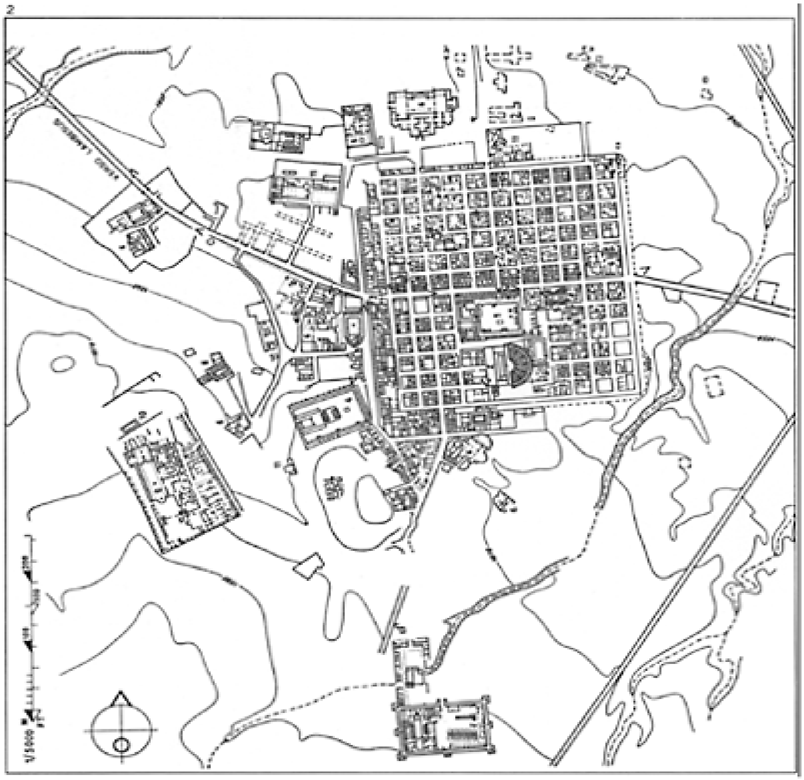
The most elementary form of angle measurement, but also the most universal, is squaring off a baseline, which enables the vast majority of buildings, centuriations and square or rectangular *insulae* to be set out (fig. 2). On the ground, two situations call for such a measurement: firstly the definition of a right angle starting from a known line marked by poles, described as raising a perpendicular; secondly, starting from an isolated point and joining up with a straight line, known as dropping a perpendicular. These different operations are usually completed by measurements of distances, which must always be horizontal for transfer to the map, the *forma*. Ranging a line and squaring off a baseline provide, by simple extrapolation, the solution to the majority of surveying problems. The instrument able to perform the two above-mentioned operations must therefore be capable of taking in two axes of perpendicular sightings, dividing the space into four quadrants: this instrument, which is the present-day optical square or surveying square was in antiquity the *groma*.

Excavations at Pompeii have greatly contributed to our knowledge of this instrument as, of the two representations of the *groma* on funerary stelae (figs 3 and 4), one is from that city and, more importantly, the only *groma* ever recovered was discovered there by Matteo della Corte, in a shop on the via dell'Abbondanza.[19] The funerary stele, recovered from the necropolis of the Nucerian Gate, is that of the *agrimensor* Nicostratus, sculpted on a plaque of marble, measuring 55.2cm long, 33.1cm high and 4.3cm thick. The central text is framed on the right by the representation of two ranging poles and a cord (the lower right-hand corner is missing) and on the left by a *groma,* the cross of which is tilted forward so that it can be clearly seen.[20] If the funerary reliefs were the only available evidence, the use of this instrument would seem problematic, since the view through the plumb lines would be obstructed if the cross had the same axis as the foot.

Fortunately, the discovery of an actual *groma* at the house of the tool maker and seller Verus (via dell'Abbondanza, Regio I, Insula 6, no. 3)[21] clarifies the actual appearance and the operation of this instrument (fig. 5).

As the principle is that of squaring off a baseline, the functional part of the instrument is formed by a cross with four perpendicular arms of equal dimensions, making up the directional square; a plumb line is suspended from each of these arms. These four lines are the *perpendicula,* forming the two sighting planes. To avoid the obstacle of the base, the square is fixed by a pivot on to a positioning bracket, at the top of the base (or upright) of the instrument. To enable the square to pivot easily, the arms have been made longer than the positioning bracket.

2



2 Timgad (Algeria), an example of the division of a city into square insulae. (L.Benevolo, *L'Arte e la citta antica,* Rome, 1974, p. 237, fig. 351.)

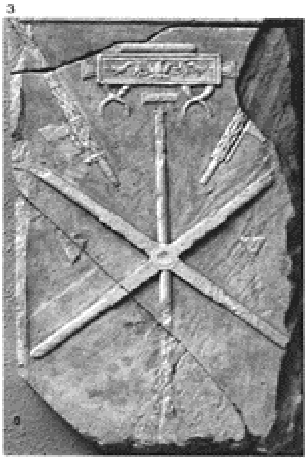
Finally the upright is provided with a point so that it can be fixed in soft ground; while on rocky ground it seems that the operator had to have a light easel or tripod available to keep the instrument standing without having to hold it all the time.[22] Setting up over a station took place in three stages: first the *mensor* secured the base of the instrument; then, swinging the positioning bracket, centred the square with the plumb line over the station to be fixed or an already existing one; and finally lined up the square on the principal axis or direction to be followed.

Aerial photography has made it possible to recover with great precision the traces of the centuriations laid down by the Roman legions,[23] particularly in arid regions or those not affected by later enclosure, and it can justifiably be concluded that the *groma* was, in such operations, the standard instrument of the military *mensores*.

The boundary stones recovered in Tunisia,[24] and more rarely in Italy, even illuminate the way in which the surveyor divided space. The *mensores* placed boundary markers at the intersection points along the two principal axes, *cardo (Kardo)* and *decumanus,* and on the right angles delimiting the centuries. On the surface of the markers they engraved the two horizontal 90° axes, the *decussis*[25] (fig. 6), and on the vertical face (the markers could be cylindrical or square) their location in relation to the *cardo maximus* and the *decumanus maximus*. The difficulty in reconstructing these today comes from the fact that the markers have often been moved (it is enough for them to have been knocked over for the original orientation to be lost). Another problem is that the surveyor, who distinguished in his text right and left (DD and SD respectively, *Dextra Decumani* and *Sinistra Decumani*)[26] did not observe a systematic polar orientation.

Joël le Gall,[27] studying the problems of orientation associated with the laying out of towns and centuriations, has established a comparative orientation table for 14 Roman survey plans (2 centuriations, 2 fortresses and 10 towns).[28] This table shows that the centuriation, but not the town, of *Augusta Raurica,* has an orientation strictly aligned to the cardinal points of the compass. The fact that the towns and the centuriations that border them, especially on rough ground, often have different orientations,[29] and the fact that the north-south and east-west axes are far from universally respected, prove that the surveyors essentially made a practical choice of orientation (fig. 7). Religious requirements, to which the Romans attributed, along with the technique of surveying, an Etruscan origin,[30] were nothing but memories that were occasionally invoked only for the laying out of temples.

Based on the indications given on the boundary stones,[31] it is possible to

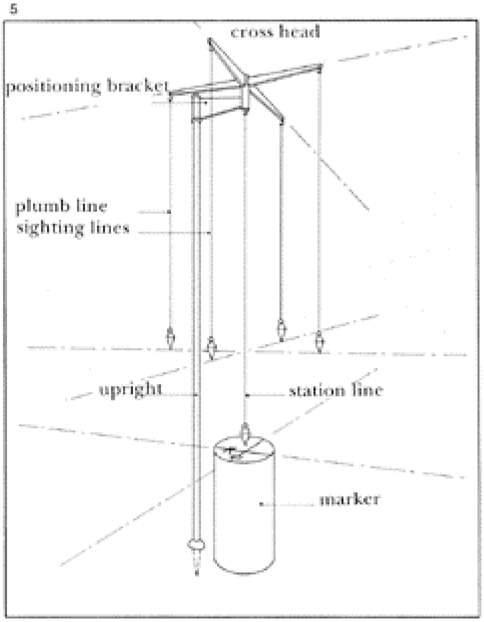


3 Funerary stele of an *agrimensor* from Ivrea (Val d’Aosta), showing a dismantled *groma* and its plumb lines.

4

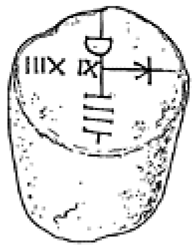
4 The stele of the Pompeian *agrimensor* Nicostratus; detail of the *groma*.

5



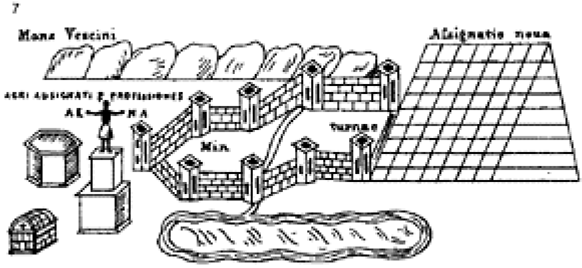
5 Reconstruction of a *groma* stationed over the centre point of a boundary stone.

6



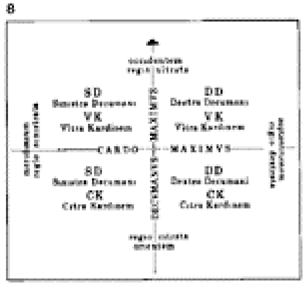
6 The boundary stone of a centuriation with *decussis* giving the orthogonal directions of the *kardo* K, and of the *decumanus* D, plus indications of distances. Diameter: 40cm; heigth: 78cm. (Museo della Civiltà Romana, room XLIII; JPA.)

7



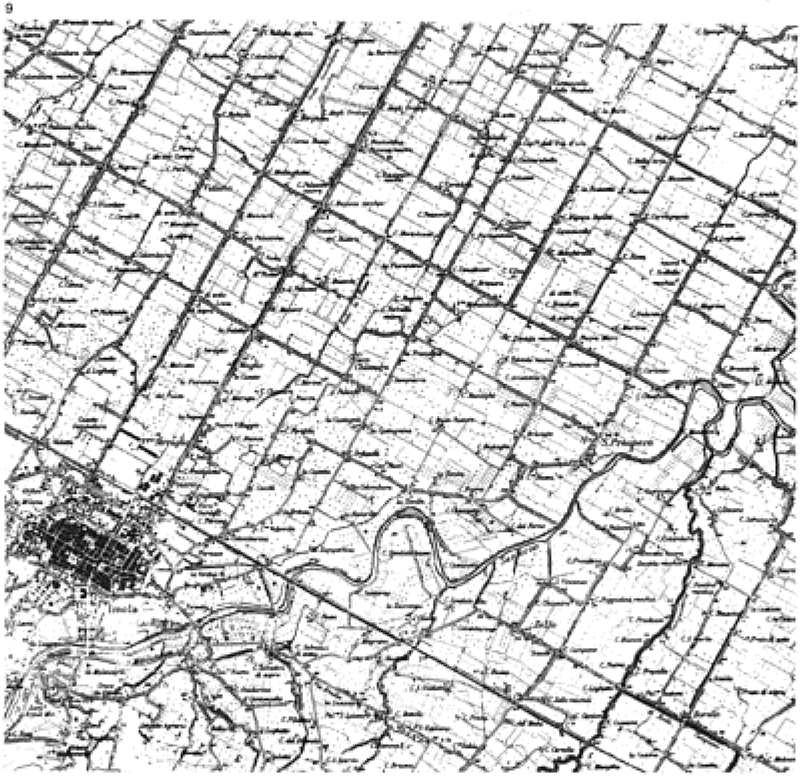
7 The centuriation of Minturno, from a drawing in the *Gromatici veteres*.

8



8 The designation of the directions and the quadrants by an *agrimensor,* looking towards the west.

propose a reconstruction of the procedure for setting up the boundary of a centuriation (fig. 8). To the initial letters of the position in relation to the *cardo* and the *decumanus* were added the numbers giving the distance of these reference points, measured in centuries. In the best examples, four markers defined 25 centuries, forming a square of 5 centuries a side called the *saltus*.[32] However elementary such operations may seem, they nevertheless constituted a remarkable achievement when the division of land extended over tens of kilometres or more (fig. 9).[33] It is probable that the *agri-*

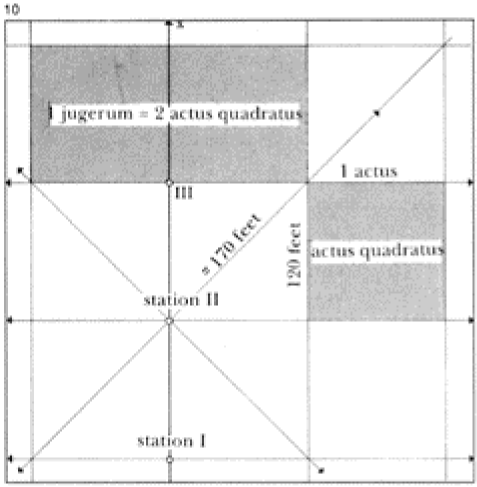


9 Map of the region of Imola *(Forum Cornelii),* crossed by the *via Aemilia*—the ancient centuriation system can still be seen in the modern road network.

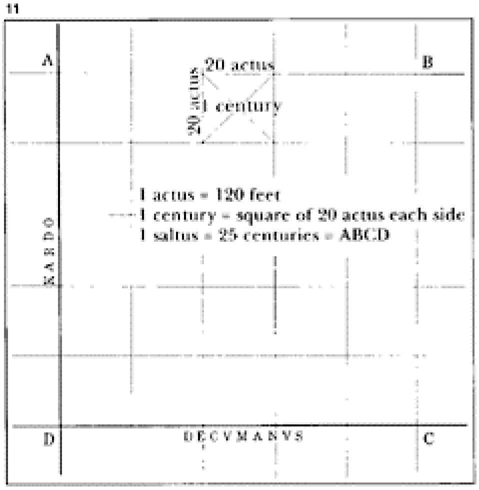
mensores, familiar with Pythagoras' theorem, periodically carried out crosschecks along the diagonal, which, for an *actus* of 120 feet square, would have had a value in the region of 170 feet (169.7). The same cross-check, applied to the diagonal of a century, had to come out at about 3400 feet (figs 10 and 11). The accuracy of the framework was ensured by the measurement of the two diagonals, which have to be equal to make a square (if there was a difference of value, the square *actus* or the century would be lozenges). The same check was of course applicable to rectangular areas.

In a commentary at the time of the publication of the cadastre of Orange by A.Piganiol, F.Salviat[34] clearly sets out the arrangement of three documents, A, B and C, describing the division of land between Montélimar and Avignon. Displayed on three walls of a room, these plans each had a different orientation when viewed straight, but when tilted downwards to the horizontal they returned to a common coherent orientation.[35] This particular example, due to the large area required by these documents and because of their being positioned on three walls, was a problem for the interpreter who did not have the key. It could possibly have led to them being understood as different topographical orientations,[36] while, as the study of F. Salviat shows, A, B and C constitute one homogeneous document in time and space. Returned to the horizontal the three plans could be read with a *cardo* oriented from east to west, and it could be presumed that the *agrimensor* had chosen for the orientation of the markers an identical west-facing position at the time of the initial survey.

In order to test the efficiency of the *groma* in a practical situation, the simplest thing was to make a life-size reconstruction of it, then carry out the linear and right-angle measurements for which it was designed (fig. 12). The



10 The process of land division using the *actus* and the *jugerum* as units of length and area.



11 A diagram of square centuriation.

instrument manufactured for this purpose was fixed on to a metal upright 190cm high (the height making it possible to sight through the lines), ending in a positioning bracket 18cm long, on which the cross-head could pivot, the arms of which were 61cm long.[37] The plumb lines, or *perpendicula,* for sighting and setting up were suspended from the ends of the arms and from their intersection.

The *groma* is set up by placing the upright near the chosen (or existing) point, at a distance not exceeding the length of the positioning bracket; then by rotating this, the setting-up line of the square is aligned with the bench mark of the station. The horizontality of the cross-head (at right angles to the upright) is checked by seeing whether one of the plumb lines is parallel with the axis of the upright. The apparatus can then be secured by a steady support (tripod) and, after first rotating the square to the required direction, sighting can be carried out. The disadvantage of this type of instrument lies, as the experiment amply showed,[38] in its great sensitivity to the wind, a disadvantage also underlined by Vitruvius in relation to the *chorobates*. However, the plumb lines are a great advantage since they enable offsets to be made at right angles even on very rough ground thanks to their height and regardless of the eye-level or the size of the operator. In a very strong wind the operator conceivably resorted to using the arms of the square directly as lines of sight.

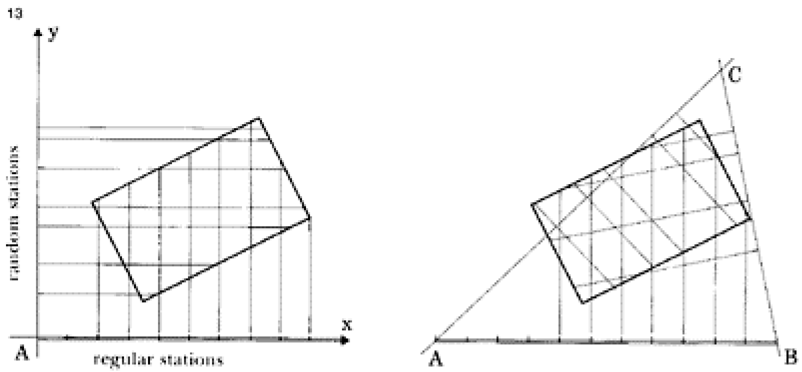
Site experiments have proved that the speed of setting up and the accuracy of the layout resulting from linear and right-angle measurements over short distances[39] was comparable to that obtained with modern instruments.

12

12 Aligning with the *groma* (Th. Adam).

The opposite to laying out was planning or topographical recording, the natural consequence of the geometer's work. The existence of topographical documents, the most complex of which is undoubtedly the plan of Rome, the *Forma urbis,*[40] unfortunately fragmentary, provides evidence of the application of this technique in the preparation of detailed plans in urban areas. It would of course be particularly interesting to know what instruments and methods were used in this considerable work, recorded on marble, and also the type of records made in the field. In the absence of these details, it is instructive to employ the *groma* for this type of work, which supports the assumption, if it does not prove it, that the instrument was used for such purposes.

Since the instrument can only measure right angles, the procedure is the same as that undertaken by surveyors with an optical square and a chain, known as planning by offsets. In this, a straight line, the baseline, is laid out with poles at intervals linked by a cord. The recording is done by moving the *groma* along the baseline (from point A in the two examples shown in fig. 13) and locating it at distances, either fixed or arbitrary, that are measured in order to plot them in *abscissa* on the recording sheet. From each of these stations two sightings are made: one aligned on the baseline AB and one at right angles along which



13 The different methods of plotting with the *groma,* with the aid of several baselines surounding or bisecting a piece of land.

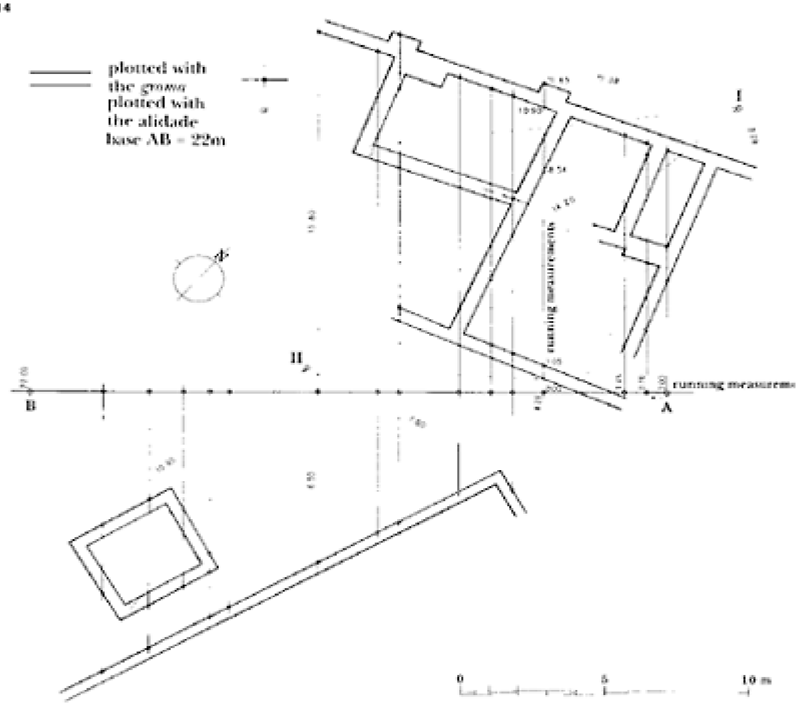
there will be one or several points to record. The distances from these points to the baseline are chained; these are the offset measurements, whose values constitute the ordinates. These measurements of distance are completed by vertical measurements (heights above the datum line), taken on the ground or the buildings themselves. The greater the number of stations, hence of measurements, the greater the accuracy of the final document, independent of that of the instrument, which depends on the quality of its cross-head. It might be thought that the risk of error would increase in proportion to the number of measurements, with a consequent loss of accuracy. In reality, the experiment shows that in working along a straight line the errors, sometimes positive, sometimes negative, occur in equal numbers and cancel each other out.

To assess the efficiency of the method the same process was carried out with the aid of an alidade and a plane-table (fig. 14). The advantage of this procedure lies in the low number of stations: only two are required with the alidade as against fifteen with the *groma;* besides, the alidade, which works by radiation, covers an area of 360 degrees and enables a considerable number of points to be plotted (except when there are obstacles), while the *groma* can plot points only in four directions per station (two in the present case). However, setting up the ancient instrument, with a little practice and in the absence of wind, can be done very rapidly and the time taken to do the same survey is practically identical. As regards accuracy it is noticeable that, on a slight slope (22m baseline and 25m ordinate), the differences are not excessive: the most considerable angular variation on a wall less than 10m long is only about 10cm at one end.[41] It is worth noting that the plan done with the *groma* was reproduced without the corrections of triangulation usually carried out.[42]

This experiment clearly showed that the method of planning by co-ordinates means that the *groma* has numerous operating possibilities in planning and laying out, such as the location of two positions for digging a tunnel from opposite ends. The *agrimensor,* when working on very uneven ground which rules out a rectilinear traverse over the obstacle, carried out a traverse with constant angular measurement[43] in the form of a series of alignments and off-sets, complemented by levelling with the *chorobates,* following the same route (fig. 15). Naturally, in the course of the operation, all the distances and changes of direction must be noted in order to return to the two original points, in the simplest case of a tunnel with a straight gallery of constant level.

The completion of the tunnel of Samos, and its difficulties, have been referred to above, but the Greeks were not the only ones to encounter difficulties in boring tunnels, as is witnessed by an inscription at Lambaesis.[44] This text relates the story of the intervention of the military engineer Nonius Datus, stationed at Lambaesis and despatched to *Saldae* (Bejaia, formerly Bougie), to take over the planning and boring of an underground portion of the aqueduct designed to supply the town with water. The work was well advanced, but the two galleries, dug simultaneously from the two sides of the mountain to be crossed, had passed one another without meeting: '…the upper part of the gallery leading southwards deviated to the right and the lower part leading northwards likewise deviated to the right; as the accurate plan had not been followed, the two sections missed one another'. Nonius Datus resurveyed the angles and calculated the levels carefully, as a result of which the job was completed in four years, indicating

14



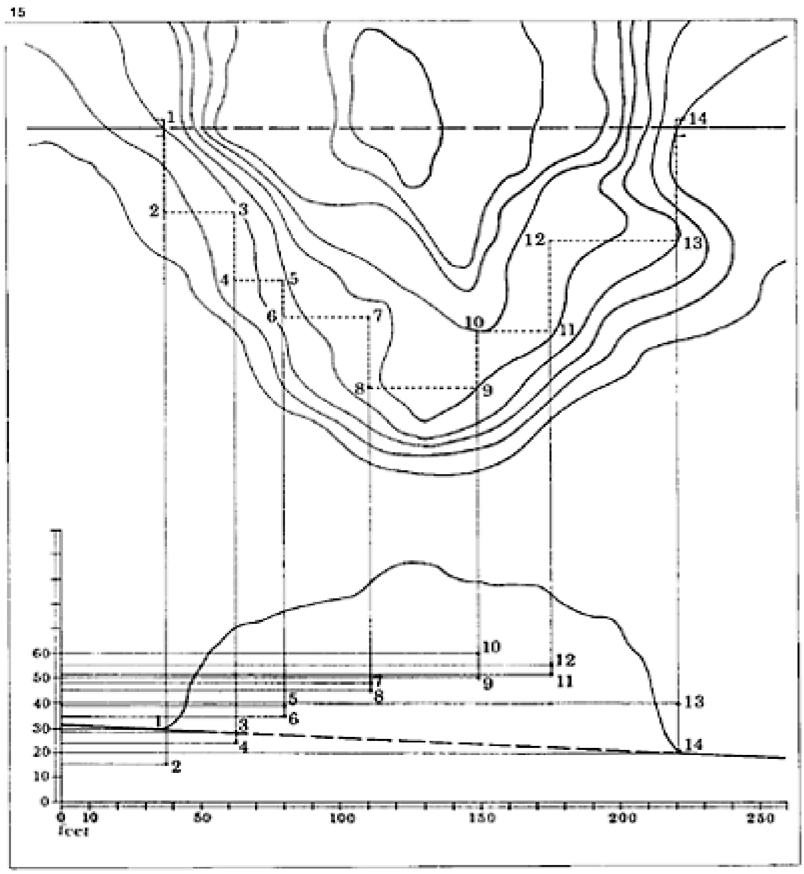
14 Comparative surveys of the same building with the *groma* and with the alidade. *Groma:* 15 stations on a single baseline AB and 51 points; alidade: 2 stations totalling 53 points.

the extent of the work needed to bore a tunnel 428m long. Despite the absence of technical details, this text nevertheless suggests that a method of planning with the aid of the *groma* and the *chorobates* by rectilinear alignment and step-levelling was used, since it says: ‘a precise line had been marked out over the top of the mountain from East to West’. From this it can be understood that the line did not go round the mountain but, as is always preferable when the relief allows, simply maintained the chosen direction over the surface, which made it possible, during the excavation, to maintain a true alignment consistently on both sides.

The technique applied here to a deep tunnel must also have been the one used in digging tunnels close to the surface. In this case boring was possible not only from each end but also through open pits along the course of the tunnel (cut and cover). The gain in time would be appreciable since, in view of the relative narrowness of the tunnels, very few workers could work at the face. An example of this technique is the large tunnel at the fort of Euryale which is not very deep and links the outer bastions to the interior of the *enceinte*. Here ten digging pits can be counted along the course of the tunnel.

Infinitely more impressive is the canal of Seleucia-in-Pieria (Cilicia), dug during the reigns of Vespasian and Titus, as commemorated by the inscription engraved on one of the walls. Partly in a deep cutting (up to 50m deep), this canal, designed to divert the course of a raging torrent, passes through two tunnels surviving in the rock. The steps leading down from the surface can still be seen, showing that the work, starting at each end, was carried out simultaneously at several different points along the course of the tunnel.[45] But the record should go to the *emissarium* (or artificial channel) of Lake Fucino (Lake Celano/Capistrano), planned by Caesar, begun in the time of Claudius and finished in 52, designed to transform a vast lake with marshy banks in central Italy into a fertile plain. The gallery, measuring 5679m, took eleven years and some 50,000 workmen to build and necessitated the boring of 42 ventilation and spoil evacuation pits.[46] A relief recovered from the channel, probably originally from the decorated outlet of the *emissarium,* shows two lifting machines with vertically positioned drums. With these a bucket full of rocks could be raised from the excavation at the same time as an empty bucket was lowered. Such mechanisms must have been in-stalled above the vertically-stepped pits to the right of the survey line. (See the illustrations in the chapter on aqueducts, below.)

Like numerous ancient cities, Pompeii has an urban layout in which can easily be detected a regular plan establishing small blocks of houses *(insulae)* separated by parallel roads in twos. This division, however, is only apparent in the areas defined at the same time as the line of the surviving wall, which is 3.2km long and was laid out in the course of the fifth century BC. The ancient town, confined to the south-western zone and including the Temple of Venus, the Civic Forum and the Triangular Forum, although integrated into the new plan, nevertheless preserved an irregular pattern of streets, even if the buildings found there, with the exception of the Doric temple, no longer belong to the Greco-Oscan period of the city.



15 Boring a sloping tunnel from two ends and planning the exits (points 1 and 14) by carrying out a series of right-angle measurements to bypass the obstacle. The sum of the off-sets must be equal to zero at the finishing point.

Pompeii was not a city on a plain but was originally a defensive establishment on a spur of lava, ending to the south with a small cliff at the foot of which flowed the Sarno. Any extension beyond this central core could therefore only take place northwards and eastwards, on a slope of Vesuvius with a significant difference in height from north to south (34m between the Vesuvius Gate and the Stabian Gate). To adapt to this topography, the new city was developed in a vaguely ellipsoidal plan, with the major axis east-west measuring 1270m and the minor axis north-south 730m.[47] The ancient city-centre was respected and outlined by two straight roads, the via Stabiana and the via della

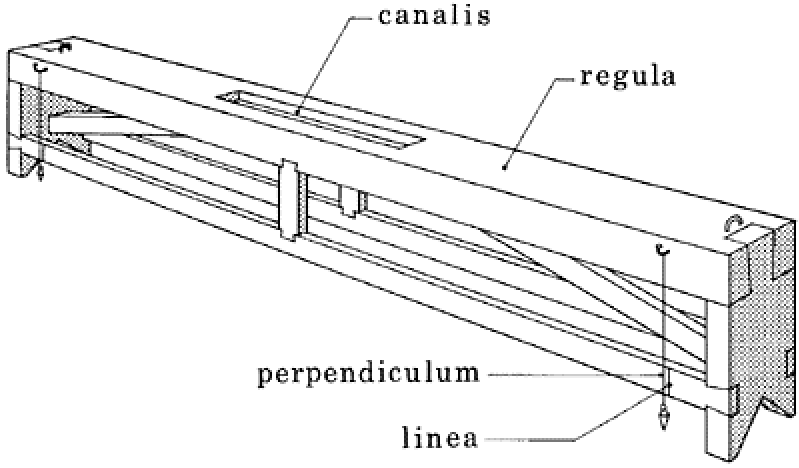
Fortuna,[48] defining a dihedron, beyond which a regular plan could be laid out. This, however, was not a simple rectangular grid but an adaptation to the slope of the ground. Six areas were defined, delimited by three roads, to which the nineteenth-century excavators gave the names in use today: the via Stabiana, now the *cardo,* via dell'Abbondanza and the via di Nola (extending the via della Fortuna) referred to as *decumanus minor* and *decumanus major* respectively (names that have today fallen into disuse).

It is interesting to note that the development of the city within this new plan took place quite naturally outwards from the ancient core, but in AD 79 the built-up area did not entirely fill the space defined by the city wall. After the Sullanian conquest, the western sector was sufficiently free of construction for the two biggest monumental complexes of the town to be laid out: the amphitheatre[49] (150×110m) and the Large *Palaestra* (141×106m).[50] Around these two complexes the individual blocks on the north and the west have revealed enormous gardens,[51] while the the first habitations discovered, such as the *Praedia* of Julia Felix (II, 4) and the House of Octavius Quartio (II, 2, 2), were completed by green areas, filling the space defined by the streets. Looking at the general plan of the town, it is noticeable that the rectangular division of the *insulae* is found only in areas I, II, III and IV, that is less than a half of the total urban area. This subdivision was altered by numerous modifications made between the initial planning and AD 79, and in fact only the axes of the roads and not the façades of the houses respect the rectangular alignments.

By contrast, the care taken over the systematic organization of a space is shown clearly by the corrected arrangement of the Civic Forum.[52] This vast rectangular and very elongated space (154×46m) was flanked in the course of the second century BC by religious, civic and commercial buildings whose somewhat haphazard layout was in fact integrated into the orientation of the surrounding *insulae* without making a regular space in the centre. At the end of the second century, a two-storey portico of tufa, erected by the Quaestor Vibius Popidius,[53] formed on three sides—east, south and west—a rectangle which was completed to the north by the Temple of Jupiter, providing the axis of the whole complex. In order to link up and align the already existing structures to the new plan, outer walls and extra thicknesses, invisible to the visitor, made the back walls of the three porticoes parallel to the colonnades.

The complement to the *groma,* the *chorobates,* is known only from a description by Vitruvius.[54] In fact, being made of wood, there is little chance that this instrument would survive.[55] Fortunately the text is sufficiently explicit for a design and then reconstruction to be attempted.[56] Designed for the task of levelling, the *chorobates* takes the form of a long bench with vertical legs, with a channel on the top. On the side are reference lines, perpendicular to the table-top,

16



16 Reconstruction drawing of the *chorobates,* based on the description of Vitruvius (VII, 5).

which are aligned with plumb-lines when the apparatus is wedged into a horizontal position (fig. 16). The channel serves as a water level, useful when the wind disturbs the plumb lines. If the dimensions given by Vitruvius—twenty feet long (nearly 6m)—are true, they are impressive, but they do demonstrate the requirement for accuracy demanded by the surveyor charged with the laying out of aqueducts. Such an object must have been very difficult to operate in the field and impossible to position on only slightly uneven ground. Besides, such a long piece of wood must have had a

17 The reconstructed *chorobates* wedged into a horizontal position.

tendency to warp due to variations in humidity.[57] It seems reasonable to suggest, therefore, that instruments of more modest proportions were also in use.

This was certainly the choice made for the construction of an experimental *chorobates,* and the dimensions decided on demonstrated the relative efficiency of an easily transportable apparatus.[58] The instrument, 1.5m long and 60cm high, was provided at one end with a footing designed to make it easy to prop up on the levelling supports (fig. 17). As any piece of ground is only rarely horizontal, the instrument is set up by placing chocks under one of the ends, flat ones at first, until it is nearly horizontal, then wedge-shaped ones, knocked in gently until the plumb-lines and the vertical lines incised on the instrument coincide; a cross-check can always be made by filling the channel with water, level with the top. Levelling can be carried out by placing one's eye at the level of the table, looking along the axis of the instrument and sighting through the two eye-holes.

Several procedures can be undertaken by the surveyor, the most systematic consisting in levelling in steps at a constant height. The top of the measuring pole need only be placed along the sight line of the operator of the *chorobates*. The difference in level will always be equal to the known height of the measuring pole, minus that of the *chorobates* (fig. 18). This method can be used on long traverses in order to simplify recording and calculation. Since on gently sloping ground this procedure is not always possible, the height would be read using a graduated pole, or as it is known today, a levelling staff (fig. 19). Because of the lack of a magnifying lens, the operator, when too far away to read the staff, sights on to a sliding marker on the staff, leaving to an assistant the task of measuring the distance between the marker and the ground.

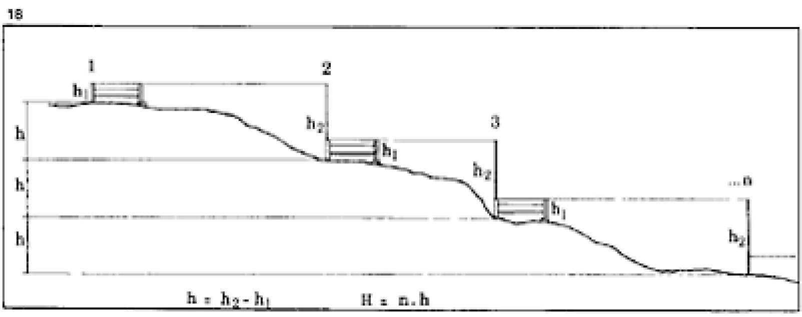
An experiment using the two methods gave the following results:

1 Step-levelling at a constant height with a pole 148cm high (4 sightings) plus a sighting on to a known height of 131cm with the height of the instrument being 60cm. The difference between the starting point A and the finishing point B, 63.5m apart, was found to be 423cm.

2 Reading off a levelling staff using the *chorobates,* with three sightings, starting from the same station and over a distance of 51.3m, gave a difference in altitude of 340cm (fig. 20). The same operation carried out with a theodolite gave 344cm.

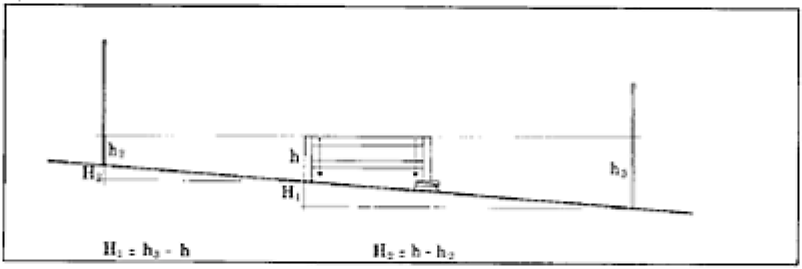
One conclusion arrived at from these experiments is that it was in the surveyor's interest to carry out a restricted number of set-ups, allowing for the limitations of eyesight. However, it must be remembered that, because the apparatus may have been subject to warping, the normal result when wood is exposed to humidity, readings over large distances are the most susceptible to error.

The main levelling operations at Pompeii were those needed to lay out a water supply network in the Augustan period. The plan developed from the line of an aqueduct, not itself an independent water conduit but a branch of the aqueduct of Serino which supplied Naples with water and finished at Baia at the gigantic reservoir of the 'Piscina Mirabile'. In the city centre the problem facing the engineers was the building of watertight channels, strong enough to resist the force of the water caused by the considerable difference of level between the Vesuvius Gate, the high point of the city where the main water distribution tank was situated, and the quarters to the south which lay between 20 and 30m below. The following drops in height give some idea of the problem:



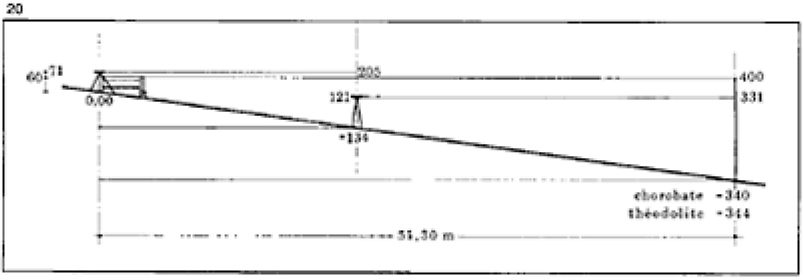
18 Step-levelling at a constant height, systematically sighting on to the head of the pole.

19



19 Levelling by backsights and foresights and measurement of the height of the point sighted.

20



20 Comparative levelling carried out with the *chorobates* and the theodolite (the vertical scale is doubled).

Great *Palaestra:* 24.5m; Nucerian Gate: 29.5m; Stabian Gate (lowest point): 34m; *Palaestra* of the Theatre: 29m; Marine Gate: 20m. The solution adopted (which will be analysed in the chapter on hydraulic installations) was the creation of a series of rises using columns supporting a tank, forcing the water-pressure to drop progressively. It was the location and estimation of the height of these columns that required the *surveyors* of Pompeii to level along all the routes taken by the water channels, in order to achieve at the end a final drop of least pressure. A check made along the course of the via Stabiana has, however, demonstrated that the first column was built too high and was therefore not very efficient since it raised the water practically back to its original height.[59]

2
MATERIALS

1 Stone

a Extraction

At the most basic level, the use of stone for building begins with the collection of surface stone fragments, rocks broken off by the action of weathering or vegetation or resulting from rockfalls at the foot of escarpments. These pieces, of varying sizes, can be used in the construction of drystone walls, the stability of which is guaranteed by the use of the largest and most regular blocks, made up of facings with an infilling of rubble. Sea or river pebbles make an ideal material because of their sizes and regularity, but their roundness means they cannot be used without mortar; it is therefore advisable to use a mortar of clay, though the two products do not always occur together naturally.

As well as this collection at source, a method still used up to the present day, architecture of quality demands the extraction from the ground of building stone that can be shaped to suit different requirements and fashions.

As with the collection of stones, extraction begins with the exploitation of surface outcrops, and numerous quarries did not go beyond this method of supply because of the abundance of rock in certain areas.[1]

The term quarry (carrière in French), referring to such a site, seems to originate in a shift of meaning of a word originally denoting a road passable for vehicles ('carossable' in French). It was probably the heavy cart designed to transport stones which gave to the source the name of the track leading to or from it. However, a derivation from *quadraria* referring to a place of squaring, i.e. stone-cutting, has also been suggested. This more appropriate etymology would seem to be confirmed by the French spelling of *quarrier* and *quarrire,* attested in the eighteenth century but which the *Encyclopédie* fixed definitively as *carrier* and *carrire*.[2] Be that as it may, it is stone alone that is referred to in *De Lapidicinis,* the title Vitruvius gives to his chapter where he deals with the places '…whence one obtains for building stone blocks as well as rubble stone'.[3] A last relic of the term is probably to be found in the medieval French word *lavier,* likewise meaning a quarry,[4] and in the phrase, *laver un bloc,* meaning to remove the rough outer surface in order to make a facing stone from it.

A builder looks for certain mechanical and aesthetic qualities from stone, and this led the Romans not only to select local material but also to import stone, sometimes from considerable distances. The physical qualities of a stone are judged by the stone-mason according to cutting hardness. This classification comprises six categories defined as: very soft, soft, semi-firm, firm, hard and cold. Thus in the first category are the cretaceous limestones or the sandstones and the less concretized volcanic tufas and in the last the marbles and granites.

In general, Roman architecture, particularly with its extensive use of rubble stone masonry, used local stone for the bulk of construction and imported only those materials intended for the noble and decorated parts (elements of the orders) or for facings. As usually only one type of stone was available in the immediate vicinity of a town or monument, its identification is relatively straightforward; the presence of marble slabs, on the other hand, calls for a complex investigation into geographical origin, bearing in mind the organized nature of the importation of this material in the imperial period.

Among the most frequently exploited or imported rocks that were highly valued are:

Marbles:
Chemtou marble, yellow veined (Tunisia)
Chios marble, grey-blue (island of Chios)
'cipollino' marble, white-yellow veined (island of Euboea)
Filfila marble, white (cap de Garde, Algeria)
Lesbian marble, white-yellow (island of Lesbos)
Parian marble, bright white (island of Paros)
Pentelic marble, white (Mount Pentelikon, Attica)
'Porta Santa' marble, polychrome veins, red-blue, violet, black, white (Iassos)
Proconnesus marble, white and white-black veined (island of Proconnesus)
Pyrenean marble, white (Saint-Beat)
'Rosso Antico', red marble (cape Matapa, Peloponnese)
serpentine marble, green (Thebes, Egypt)[5]
Thasian marble, white, coarse-grained (island of Thasos)

Other rocks:
alabaster, white (Thebes, Egypt)
black basalt, green basalt (Upper Egypt?)
grey granite, black granite (Aswan)
pink granite (Aswan)
red porphyry (Egypt)
green porphyry (cape Matapa, Peloponnese)

The Italian peninsula itself possesses fine stones, the most famous being the marble of Carrara, which exists in two varieties—white 'Lunense' and grey-blue 'Luna'. The exploitation of this stone became an imperial privilege under Tiberius. Another Italian stone is the Roman travertine extracted from the Tivoli quarries.

The stones used to make rubble are innumerable and, as already noted, of local origin. At some sites, however, different stones, sometimes in large numbers, have been found and it is useful to list those found at the exceptional cases of Rome and Pompeii.

Rome: Seven kinds of volcanic tufa (Anio, Campidoglio, Cappellacio, Fidene, Grotta oscura, Monteverde, Peperino)[6] to which must be added travertine; i.e. eight varieties of building stone.

Pompeii: Hard lava, honeycomb lava or scoria, volcanic tufa (Nuceria, Pappamonte, giallo), calcareous tuff; i.e. six local rocks to which are added the imports.[7]

When several sources are available locally, builders have the freedom to use stones according to their qualities or appearance, for example using hard lavas mainly as paving stones or for foundations and tufas in the body of the masonry.

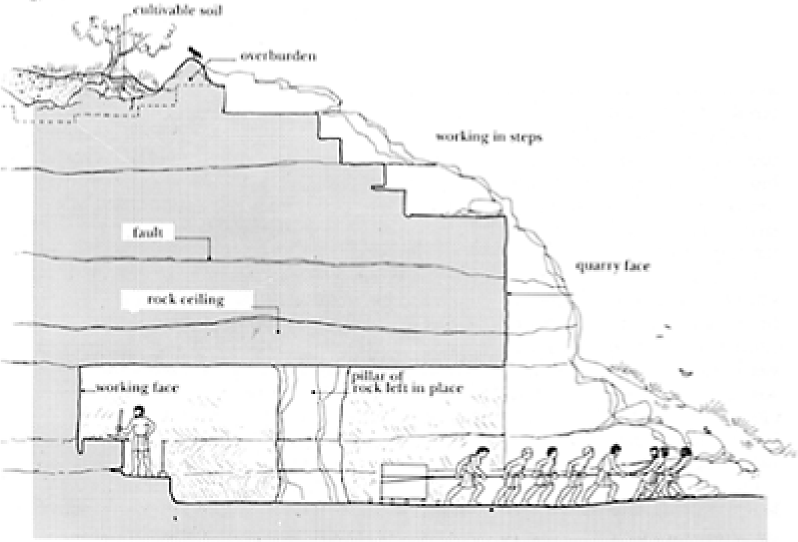
Vitruvius makes some observations relevant to this:[8] 'The stones which are not hard have the advantage that they can be easily cut and are good when used in covered places, but placed out of doors, the frost and rain turn them to dust…'[9] Further, he recommends stone from 'the territory of the Tarquins' (the region of Bolsena) which ages well, even the finest mouldings: '…one sees great and fine statues, small bas-reliefs and several very delicate ornaments representing roses and acanthus leaves which, notwithstanding their age, have all the appearance of having just been finished quite recently.' Finally, he advises, when using soft rocks and volcanic tufas, to '…take them from the quarry in summer and not in winter and to expose them to the air in a covered place two years before making use of them…' As a result of this precaution porous rocks lose moisture, called the quarry sap, and those not resistant to the weathering due to exposure outside can be rejected.

With experience, the quarry master recognizes in the field, especially in cuts made in the rock, the strata unsuitable for building stone. With surface quarrying, the first step is to remove a superficial layer, sometimes itself covered with earth, which is subject to weathering and plant infiltration and called the overburden.[10] The overburden may include a lower layer useful for producing pebble stones. The upper layer can therefore be distinguished by the term dirt bed.[11] Once the overburden has been removed and the quarry master has exposed the rock mass, exploitation can begin (fig. 21).

The quarry master can sometimes make use of the natural strata to remove blocks that can be shaped and transported. Fissures may outline a volume of rock which is already detached, so that it can be extracted simply by forcing with metal wedges and crowbars. This method is only rarely possible, however, and work usually takes the form of cutting grooves into the rock to define blocks which, when extracted have a shape and size approaching those needed. This common process makes for both an economic use of material and a considerable saving in the time taken in cutting (figs 22, 23).

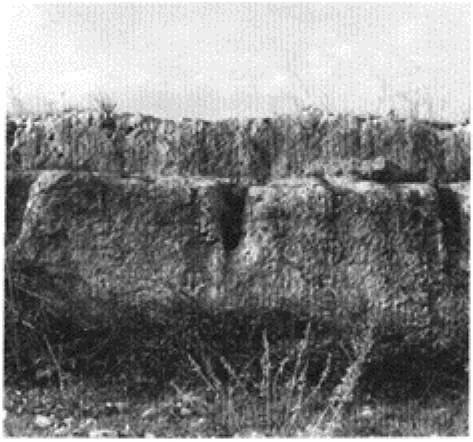
After exposing a vertical face (an operation usually assisted by a natural incline) and a horizontal face, the quarryman would cut, to right and left, incisions the same depth as the height of the block required, and then another marking the back face. These

21



21 Diagram showing different types of quarrying.

22



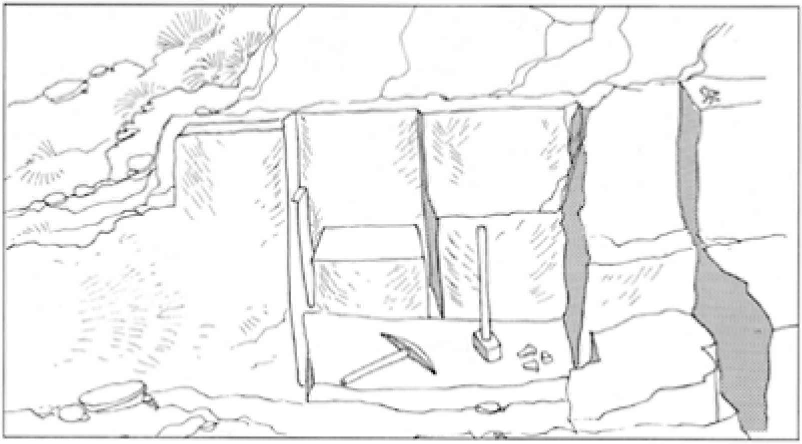
22 Preparatory grooves in the quarries used for the walls of Syracuse.

narrow grooves, forming the undercutting, were made with a pick *(fossaria dolabra)*[12] which left concave furrows corresponding to the quarryman's hand movements. The grooves could be enlarged for access when the block to be cut out was of a considerable size. Thus at the quarries of Cusa (Selinunte) the grooves surrounding the column drums are 85cm wide at the top and 55cm wide at the base, enabling the quarryman to get in and work. A final groove was made under the block by forcing in metal wedges *(cunei)* with a mallet *(mallei);* the operation was made easier if a fault or a line of natural stratigraphy was encountered. When the cuts were deep enough it was sometimes possible to use a crowbar to finish detaching the block thus outlined in the rock mass. If wedges were used, one of them was struck very hard to cause a fracture as far as the back cut.

In some cases the quarrymen used wooden wedges, a technique common in certain quarries until the eighteenth century.[13] Very dry wooden wedges were forced into the cracks, then soaked with water and covered with wet cloths; the capillary action slowly caused the wood to swell, thus loosening the stone block.

Quarrying took place in steps, at least one course high. Depending on the duration of the quarrying

23



23 Method of extraction of square blocks at the ancient quarry of St-Boil.

operations and particularly if the vein of rock went down a long way, traces of ancient workings are relatively rare. What survive mostly are the steps, with deep drops, or vertical walls resulting from the continuation of quarrying downwards.

An example found in Sicily, though borrowed from the Greek world, perfectly illustrates this type of extraction. Quarries were opened there during the reign of Dionysus the Tyrant (405 to 367BC) in order to construct the formidable wall, 27km long, designed to protect the city of Syracuse.[14] (The wall enclosed an important extra-urban zone reserved for cultivation in the event of siege and never actually built on.) The quarries were never used for anything other than the provision of the stone required for the wall and were abandoned after it was built. On this site, quite exceptionally, the steps resulting from the extraction can be distinguished for several kilometres, showing clear traces of the preselection of blocks of uniform size, detached from the rock using outline grooves and wedges forced into the lower part.

Certain large, isolated monuments had particular quarrying operations associated with them which were not continued, owing to both their distance from any large settlement and the presence of other well-situated deposits near at hand. In Roman Gaul the most interesting example is provided by the Pont du Gard, the stones for which were extracted from the banks of the river a few hundred metres to the north of the building site.[15]

The two methods of extraction, using natural fissures and strata, and undercutting the edges combined with the use of wedges, were standard, and there is hardly an ancient quarry where the traces of these workings are not visible. It is still easy to imagine the great activity at many sites that were abandoned in the course of quarrying operations for a variety of reasons that cannot now be established with certainty. Numerous prepared blocks can be found in all quarries, not only at Syracuse where there is a whole host, but also at Barutel (quarries of Nîmes),[16] Saint-Boil (Saône-et-Loire),[17] Boulouris (Var),[18] Monte Lepino (near Segni), Gabii (Latium) and at Cerveteri.[19]

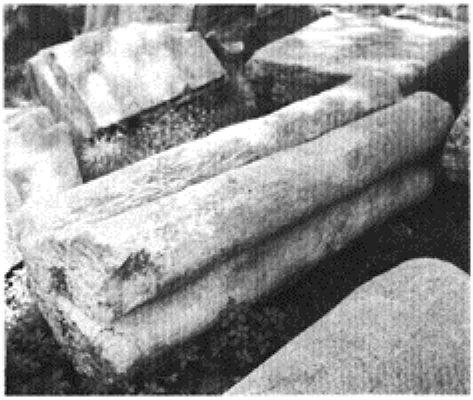
The extraction of blocks either for use in coursed masonry, or of manageable size intended to be split up (rubble stones) or shaped (mouldings, drums) was not the only task of the quarrymen. The desire for technical achievement, and the practical spirit that went with it, encouraged the Romans to extract from the rock large architectural pieces, not only in the form of rectangular blocks (for megalithic courses on monuments in the eastern empire and architraves), but also columns of all dimensions, usually of marble and granite. These columns are still visible in the Pantheon (granite), in the Temple of Venus and Rome (granite), at the Basilica Ulpia (granite and "cipollino") and at the Temple of Antoninus and Faustina ("cipollino" marble), to mention only examples in Rome.

Although the technical accomplishment is evident, given the scale of the majority of these works (12m high and 56 tonnes in the case of the Pantheon), it also seems certain that mastery of handling and transportation made such grand achievements commonplace, and in the case of smaller pieces, facilitated the work of extraction and transport. A particularly spectacular demonstration of this comes from the depot of imported marbles in Ostia, where considerable quantities of materials have been recovered, waiting for delivery to the user. Among these blocks are several bundles of marble columns, still joined together in groups of four just as the quarrymen had extracted them from the rock (fig. 24)

In quarries the sites corresponding to the removal of the shafts can be traced in the rock, as for instance at Chemtou (Tunisia) (fig. 25) or at Aliki (Thasos).[20] Sometimes the columns themselves have remained in place, partially or totally detached, as in some quarries in Sardinia[21] or again at Aliki. In the Greek quarries of Selinunte (the so-called Cave di Cusa), which deserve a mention despite being earlier (sixth-fifth century BC), several column drums intended for the gigantic temple G are still visible at different stages of extraction. The work in the quarries here is as spectacular as the building of the monument itself, since the blocks were cut from the rock in a roughed-out form ready for use (fig. 26).[22]

When considering the sudden abandoned state apparent at a number of places it is useful to make comparisons with modern-day sites of the same nature. For instance, the limestone quarries at the foot of Ventoux, near Malaucène (Vaucluse), abandoned for only two generations, illustrate that the quarrymen had left in place material with no thought of ever salvaging it and that the work of extraction was interrupted in different parts at different stages of progress. In studying another activity, woodworking, the author has been able to show through an investigation into water-powered

24



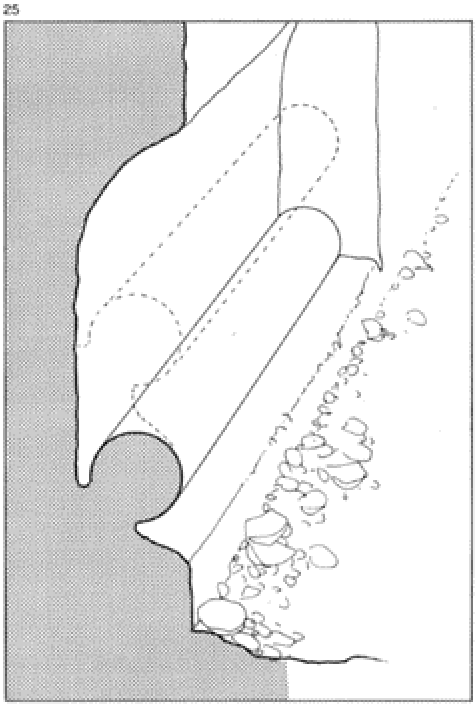
24 A group of four columns, still joined, found in the port of Ostia.

saw-mills, that numerous mills had been abandoned by their owner, on his retirement or death, leaving all the material and the tools in place, including logs that were partially cut and still under the saw. Now, in neither of the two examples mentioned above had a sudden catastrophe occurred to interrupt or destroy the local economy. The end had come quite naturally with a simple cessation of activity. This observation does not exclude other explanations for other situations, but it may moderate hasty conclusions which invoke a human or natural cataclysm to explain the interruption of work in progress at a quarry or building site.

When working in steps reached the lowest level at the foot of a natural incline, quarrying continued by descending vertically on one or more working faces, progressing in heights of courses, using the same method as before. Once the courses had been removed, a vertical cliff remained, the quarry face, in which the imprint of the courses can be clearly traced (fig. 27). The tufa quarries in the area around Rome, where activity continued for centuries, are all similar and the regularity of the extracted courses means that their height can be ascertained—usually between 60 and 65cm—a simple choice of measurement from which it can be concluded that the blocks were 2 feet high (fig. 28).

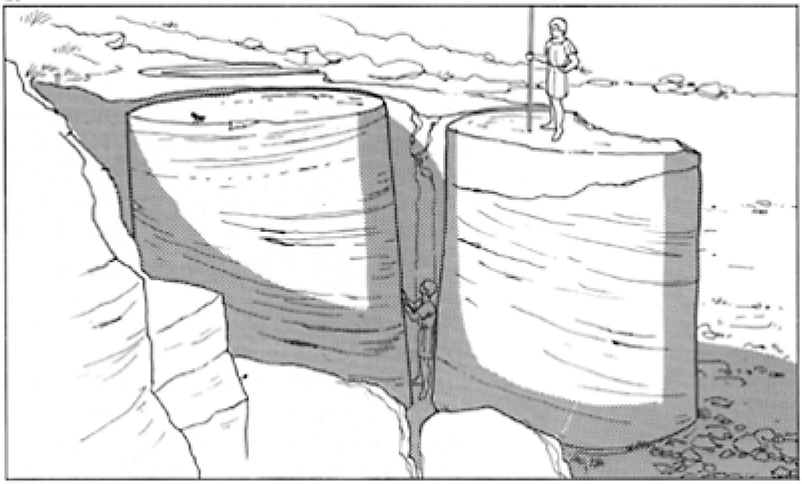
The vertical descent of a quarry

25



25 The method of extracting column shafts in the quarries of Chemtou (Tunisia).

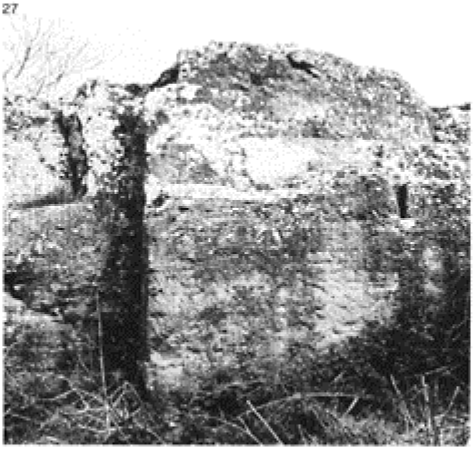
stopped when the rock vein came to an end due to a change in the subsoil; when, as frequently happened, an underground water level was encountered; or simply when lifting the material from the bottom of a very deep hole became a problem. When this occurred the rock mass was reached by means of tunnels *(fossae),* a much less productive process, for the obvious

26


26 Drums intended for Temple G at Selinunte, still in the quarry at Cusa.

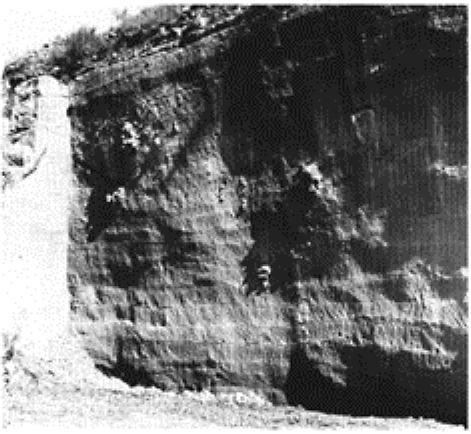
reason that the majority of the rock has to stay in place to provide support and roofing (figs 29, 30).

Depending on the type of rock, the cavities left by working look completely

27


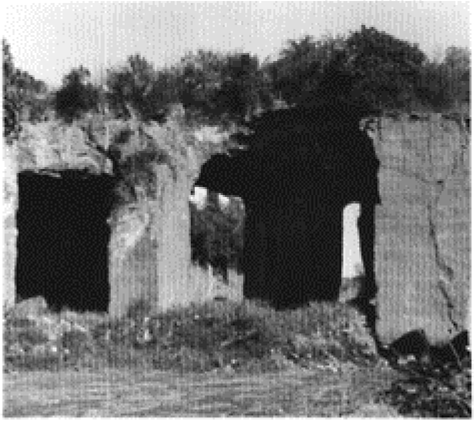
27 Quarries at Gabii (Latium); the step workings become a vertical wall.

28



28 Quarry face in the tufa of the Anio Valley (Latium); the traces of cutting the rock in regular courses can be clearly seen. Note the overburden above.

29



29 Quarrying into the rock in halls and galleries; the tufa of the Anio Valley (Latium).

different. When the natural strata are approximately horizontal and are split by breaks which occur relatively closely (2m or less), the quarryman often digs low tunnels of average working height, taking care always to leave above him at least one, and usually two, natural strata, forming the quarry roof. In order to enlarge the workings, chambers are opened out, supported at regular intervals by rock masses left in place; these pillars are sometimes built of rubble stones to hold up a fissured roof.

Cutting underground used the same methods as in the open air. However, when the tunnel or chamber was low, the blocks extracted were of full height, and this was done by undercutting the front and the sides, with the final removal by forcing with wedges being necessarily decisive as it was the only way to get at the inaccessible back face.[23]

When the rock deposit was very deep and there were no lines of breakage or fracture, the work was in many respects easier as it was possible to open sizeable chambers, needing only widelyspaced pillars. Work at the rock face then proceeded in that same way as outside, in steps descending vertically.

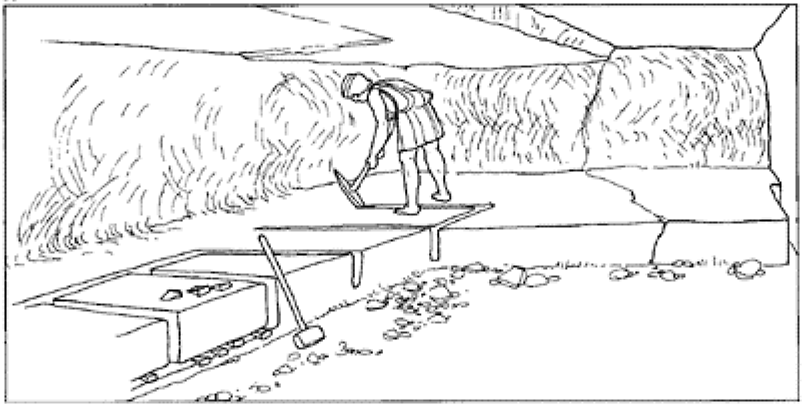
More than tools for working wood, tools for stone become blunt and lose their edge. The quarrymen themselves saw to the maintenance and upkeep of their equipment, as they still do today.[24] All quarries of any size had a small forge where damaged metal pieces could be rehoned and sharpened. Traces of such activity are only uncovered when layers of debris and rock falls are removed, and generally consist of piles of cinders and hearth remains, often spread over different areas following the movement of the workings, as was probably the case at the quarries of Barutel[25] and Aliki.[26]

The distance between the extraction site and the building work was naturally of concern to the builders. A number of towns were fortunate enough to discover in their own subsoil the material or materials necessary for their architectural genesis—for instance Rome, Naples, Syracuse, Paris and Lyon, at least at the beginning. However, this was only rarely the result of a planned decision since Roman towns, in the peninsula as well as in many parts of the Empire, were only enlargements of earlier settlements built on sites chosen for their strategic or commercial value.

With the development of monumental building programmes and the demands of monumental decoration, quarries were opened almost everywhere where deposits of building stone appeared in any quantity, as far as possible with an eye to the proximity of a land, river or sea route for its ex-ploitation. Special arrangements were made to obtain access to a working site, sometimes crossing very rough terrain as was the case for the marble quarries of Pentelikon and Carrara.

As the marble quarries on the slopes of Mount Pentelikon were quite high up, the transport of the blocks, as at Carrara, was achieved by means of a descent road that has been located and exposed for most of its route towards the plain.[27] This road, paved with marble and laid out almost in a straight line, in fact formed a slipway, comparable to the runways used by Alsacian timber-sledges. Holes dug in the rock on both sides of the road at regular intervals were sockets for heavy wooden bollards around which the quarrymen wound the ropes designed to brake the descent of the sledges loaded with marble (fig. 31). At Carrara, the ancient tracks have disappeared, but until the last war blocks were carried down on large carts or sledges for the heaviest blocks, pulled by a variable number of oxen pairs according to the load. It was in this manner that in November 1928 the gigantic monolith was transported,

30



30 Reconstruction of quarrying in galleries in the tufa of Grotta Oscura (Latium).

31

31 The descent of marble blocks from the quarry on Pentelikon. (After A.K.Orlandos.)

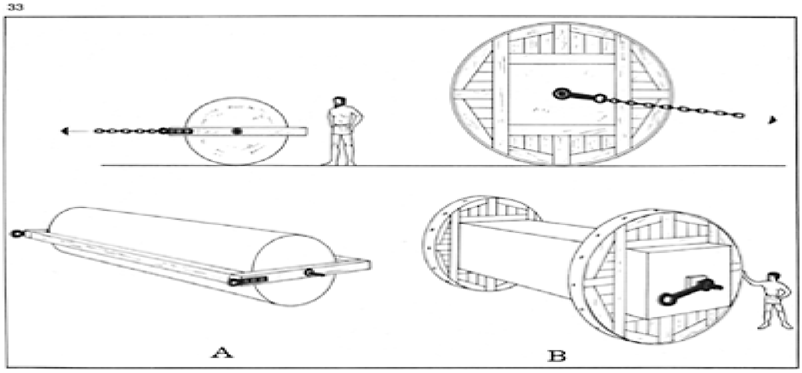
32m long and weighing, with its sledge, in the region of 600 tonnes, destined to become the obelisk of Mussolini erected in Rome in front of the Olympic Stadium (fig. 32).

This transport, by the simplest of means, of such a mass of rock, comparable to the largest stones used in antiquity, helps considerably towards the solution of the problem, which for many has all the attractions of a mystery, of how the heavy blocks were moved. The technical knowledge of the Greek and Roman periods, following trials and experiments made over generations, enabled them to overcome obstacles presented by the

32

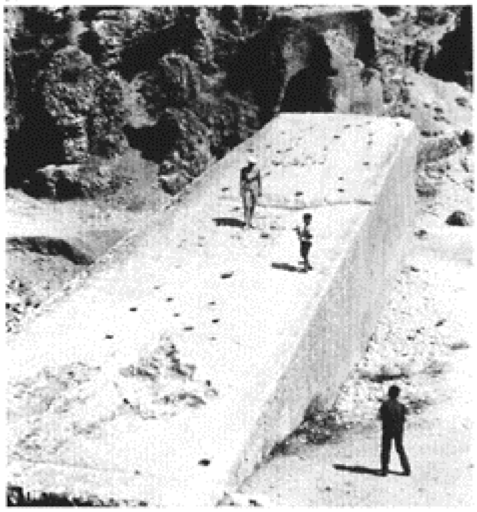
32 Mussolini's monolith being transported on a sledge, pulled by a team of sixty oxen, Carrara, 1928. (Photo: Hrand.)

33

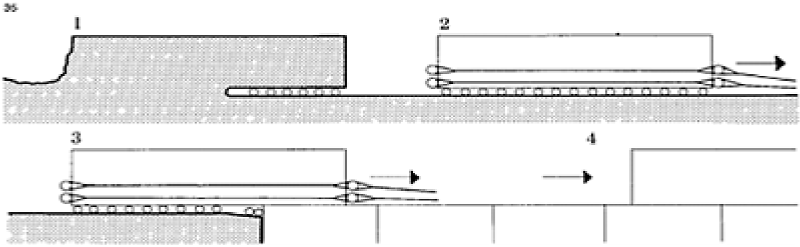


33 *A:* The device of Ctesiphon; *B:* Metagenes' machine. Methods of transporting column drums and

architraves for the Temple of Artemis at Ephesus and Temple G at Selinunte.



34 The ‘southern stone’ still in the quarry at Baalbek, measuring 21.5×4.3×4.2m, and weighing 970 tonnes.



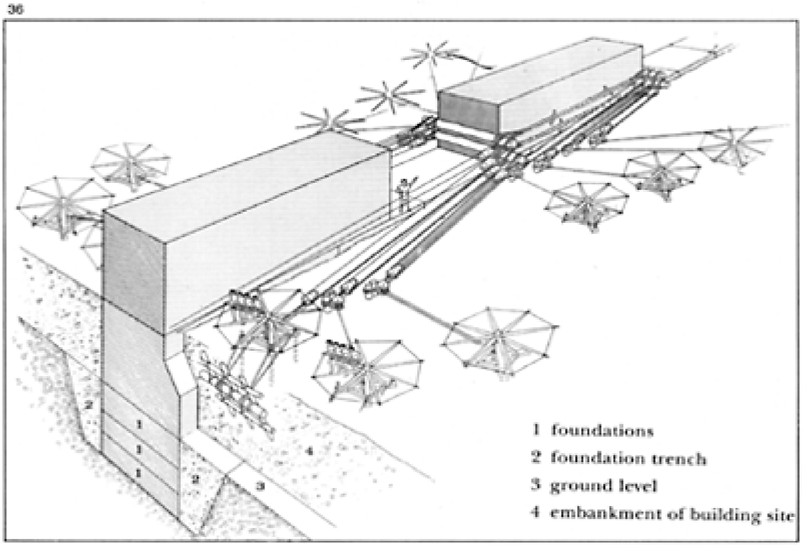
35 Diagram showing how the lower surface of the megaliths at Baalbek were gradually freed and rollers for transport progressively positioned under the blocks.

transport from quarry to site of blocks as impressive as those used, in the sixth century BC, the temple G at Selinunte or, later, the podium of the Temple of Jupiter Heliopolitanus at Baalbek.

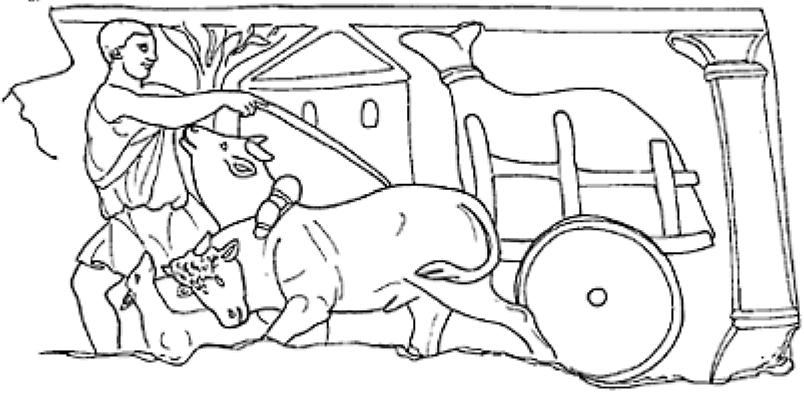
At Selinunte the methods employed for the transportation of column drums—twins of those left in the quarry at Cusa—and of architraves, can be traced in the stone. They take the form of holes for fixing the means both of attachment: axles inserted at each end for the drums; and of transport: wooden wheels encircling the blocks, both of them then drawn by oxen. Such methods are also mentioned by Vitruvius as having been used for the construction of the Temple of Artemis of the Ephesians (fig. 33).[28]

At Baalbek, the builders took on a supreme challenge to human ingenuity by building a podium with decorative facings all of colossal dimensions.[29] The largest are the three trilithons measuring respectively 19.6m, 19.3m and 19.1m long by 4.34m high and 3.65m deep. Their average weight is in the region of 800 tonnes. As the quarry was situated around 800m from the temple and slightly higher up, the megaliths were brought on a track, the path of which was adapted to the bedding level of each course so that there was no raising operation needed. One of the stones left in the quarry shows how they were placed on rollers gradually as the lower face became exposed (figs 34, 35). For the transport itself, capstans attached to pulley blocks placed symmetrically on both sides of the load ensured the slow progress of the enormous block.[30] Sixteen of these machines, each one operated by 32 men (making a total of 512 men) and developing a power of more than 10 tonnes, provided a draught force, multiplied by the pulley systems each with four pulleys (and affected by a large coefficient of friction), of 557 tonnes, or approximately $\frac{2}{3}$ of the load (fig. 36).[31]

36



36 Reconstruction of the transport of the trilithon blocks at Baalbek.



37 The Roman method of transport by chariot with solid wheels with projecting rims; the oxen are attached by a neck yoke. (Museo Nazionale; JPA.)

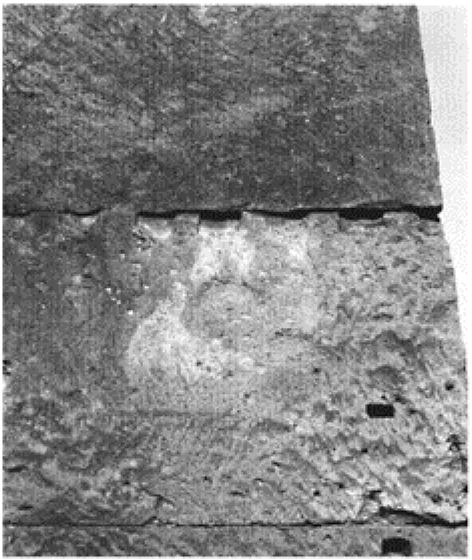
Apart from these exceptional situations, transport was by carts pulled by oxen, the use of which is already attested in the Greek period[32] and which Roman iconography portrayed, particularly in the case of the transport of materials in bulk (fig. 37).[33]

b Stone-cutting tools

As has already been noted, when blocks of stone were being cut out they were often given a roughed-out form as near as possible to the final size so as to simplify and lighten the burden of transportation; they could also take the form of a rectangular block much larger than the blocks in coursed masonry, but easy to divide into smaller parts. Unshaped blocks removed from the mass along natural fissures were also given some sort of roughing-out after being extracted.

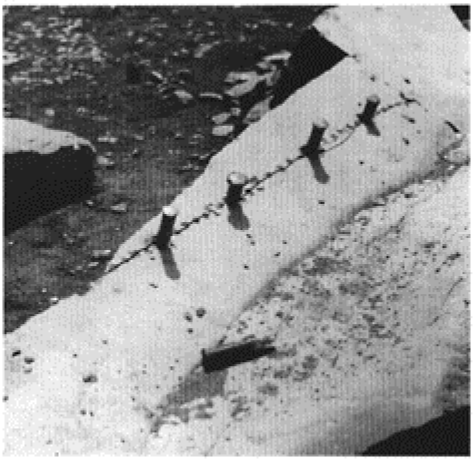
To split the blocks up the same method was used as that for extraction—driving wedges into holes made along the line of the break. To do this the quarryman first drew chalk lines on the best cut face; then sockets for the wedges were made along each of these lines, using a chisel and a mallet, and the wedges were put in place. A series of pick marks was then made between each wedge to indicate and create the line of breakage and, finally, the

38



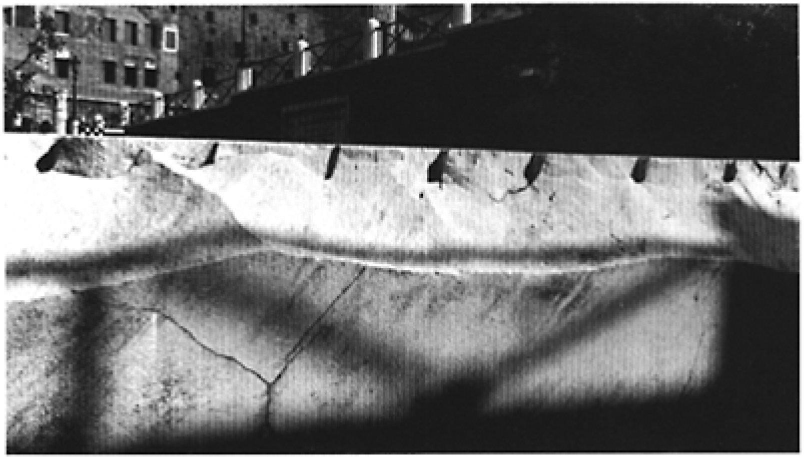
38 A block of tufa with the traces of the sockets for the wedges that were used in cutting it up (Pompeii VIII, 5, 30).

39



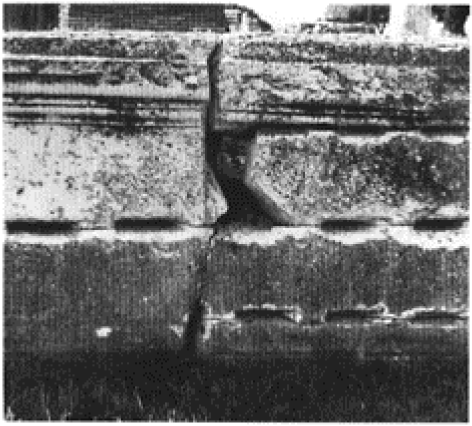
39 A line of breakage veering off on a block of lava split with wedges. Terzigno (Campania), 1980.

40

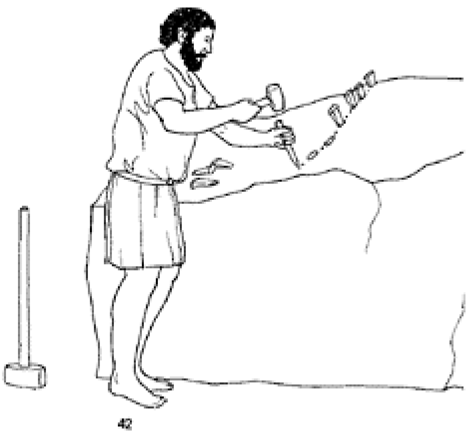


40 A failed attempt at separating a marble architrave with wedges, later reused in the Later Empire. Trajan's Forum, Rome.

41



41 A block of marble prepared for separation with wedges, so that it can be reused. Forum of Ostia. The wedges are 18 to 20cm long and 4 to 5cm high.



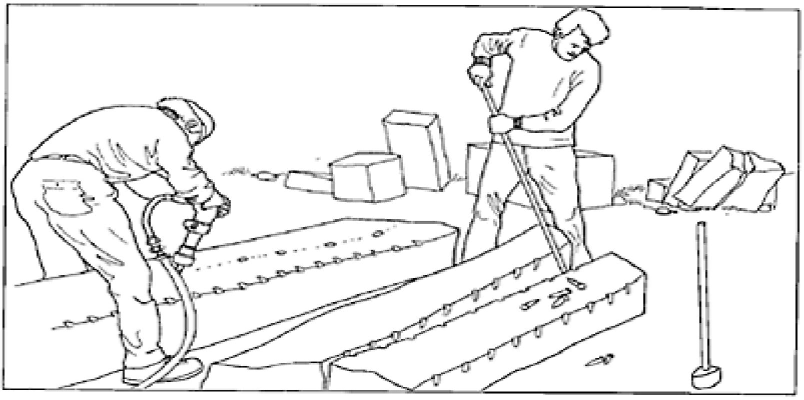
42 Drawing showing splitting a block using wedges.

middle wedge was struck a hefty blow with a mallet, achieving the opening of the rock.[34] The efficiency of the technique is such that the break, particularly in hard rocks, results in perfectly cut surfaces sometimes adequate for using in a final form (figs 38, 39, 40, 41, 42, 43).

A saw, more generally associated with woodwork, was quite widely used to cut up large blocks. The accuracy of this method was in fact not much better than that usually obtained using wedges, but it avoided the risk of making a mistake in cutting. It is not rare to find rocks cut using wedges abandoned as a result of a considerable deviation from the break line, caused by an internal cleavage not visible on the surface. An excellent example of an accident of this type is visible in Trajan's Forum in Rome, where an enormous marble architrave was salvaged in a later period and an attempt was made to divide it with wedges; but the break, instead of following a vertical direction, deviated at an angle of 45°. It is understandable that, particularly when cutting up a valuable rock like marble, stone-masons often preferred to use a saw *(serra, serrula),* making the work much longer but less prone to accidents.

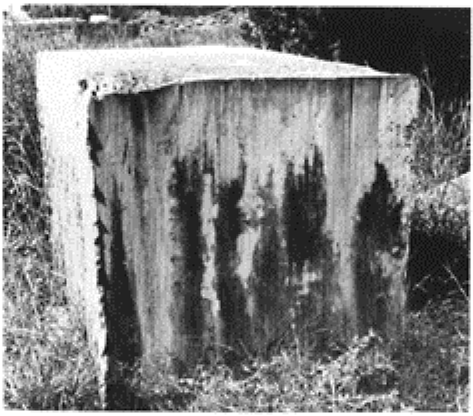
When cutting a relatively soft stone, the blade of the saw was serrated, with nothing to distinguish it from a woodsaw; for hard rocks a smooth blade was used with an abrasive (sand).[35] In both cases the line of cut was prepared with a point so that the saw did not deviate and, during the operation, water was poured along the groove to avoid overheating the blade. The saws used were a type of two-handed saw, provided with a pulling handle at each end; the irregular tension of the blade, as well as its path, subject to the steadiness of the movements of the workmen, have left quite typical marks on the stone. However, these are visible only on the back surfaces of blocks or on

43



43 Splitting blocks of granite in a quarry in Brittany. The principle is the same, but the pneumatic drill replaces the mallet and punch.

44

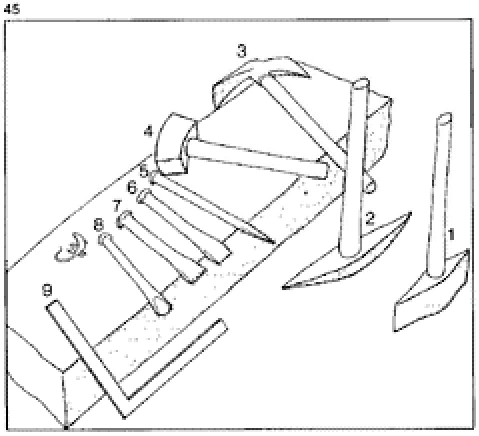


44 A sawn block of marble on the building site for the Temple of Venus at Pompeii.

unfinished stones that were abandoned at the work place or building site. In many respects the site of the Temple of Venus at Pompeii, interrupted by the eruption of 24 August 79, offers the best examples of stone cutting using different tools and at different stages of completion, with, among other things, several blocks of marble sawn and stored together awaiting their use in finished form (fig. 44). For large blocks the blade of the saw was kept tense by a wooden frame which could be suspended from a portico in the case of the largest saws, as has been suggested in the reconstruction of the quarries of Dokimion.[36]

Once the block had been squared, either at the time of extraction or after

45



45 The Roman stone-mason's essential tool kit: *1* cutting hammer; *2* scabbling hammer; *3* kivel or stone-mason's hammer; *4* mallet; *5* punch or point; *6* straight chisel; *7* claw chisel; *8* gouge; *9* square.

46

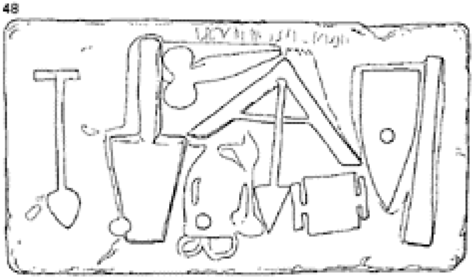
46 The principal tools of the stone-mason remained the same from the Roman period up to the twentieth

century. *Top:* two mallets; *(below, from left to right):* a punch; three chisels; a mallet-headed chisel; a driver; a claw chisel.

47

47 A scabbled stone block in the process of being squared on the site of the Temple of Venus at Pompeii.

48



48 Relief of Diogenes Structor, a Pompeian mason, showing a plumb line, a trowel, an apotropaic phallus, levelling square, stone-mason’s hammer or kivel, a chisel and two objects difficult to identify, possibly an amphora and a plasterer’s tool.

cutting up, the stone-mason gave it its final shape using different tools, the size and form of which vary according to the fineness of the desired appearance. According to a classification established by A.Leroi-Gourhan,[37] two major categories can be distinguished: tools of direct percussion (‘percussion lancée’) and tools of indirect percussion (‘percussion posée’). In the first category the tool is used alone and has a blade with a handle, giving it the shape of an axe or a hammer. The blow against the stone is violent and lacking in precision, thus these tools are used for squaring and for the rough shaping of facings. In the second category the tools are used in pairs, with one placed with its point or blade on the surface and hit with a percussor: the mallet or stone-mason’s hammer (figs 45, 46).

The first and the most primitive tool of direct percussion is a pick with two points. This is also used for cutting out but for shaping is generally of smaller size. It is called a scabbling or spalling hammer and its use leaves marks showing the manner in which the stone was worked. For instance when the workman hits the stone vertically, he makes chips fairly close to one another, creating a facing that is pock-marked and rough (fig. 47).

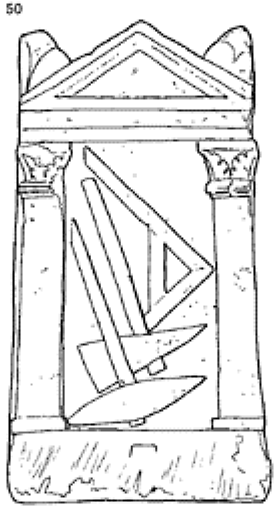
Known since the Middle Ages, the stone-hammer,[38] smaller than the pick, appears in two forms. It can either have a head with one end squared with two edges and a point at the other end; or the point is replaced by a blade with the edge parallel to the handle.[39] The stone-hammer in either of these forms cannot be verified in Greek or Roman antiquity—the archaeological record has not yet come up with objects of this type and the sculpted representations, however numerous they may be, are lacking in detail. Nevertheless, three representations can be mentioned that do give some cause for conjecture: the first is the stele of a craftsman found at Pompeii (fig. 48) at the House of the Cock,[40] which shows a view from above of a tool likely to be a stone-hammer (the outline not making it possible to establish whether, at one of the ends, there is a point or a blade); the second is a relief found at Terracina showing a scene at a building site with two workmen working a stone with hammers which are as likely to be mauls as stone-hammers;[41]; thirdly there is a painting from the House of Siricus at Pompeii (VII.1,25)[42] showing the building of a town wall on which two stone-masons are using a stone-hammer.

By contrast, there are numerous examples of hammers with two points which are in fact small scabbling hammers (fig. 49) and hammers with two cutting edges *(dolabra)* similar to two-bladed axes.[43] But the reliefs do not make it possible to distinguish, when these tools are seen in profile, whether what is intended is a double-bladed stone-hammer or a maul; it can only be assumed that if it is shown beside a chisel, the tool is in fact a percussor (figs 50, 51, 52). The cutting hammer sometimes has one blade with the same axis as the handle and one which is perpendicular, in which case it is called a kivel or stone-mason’s axe. This dual arrangement is a great advantage to the stone-mason who can

49 Stone-masons preparing stone blocks; their tool seen in profile could be a scabbling hammer (with two points) or a double-bladed stone-hammer. In the basket are the finished products. Relief from a tomb on the Isola Sacra, Ostia (drawn by JPA).

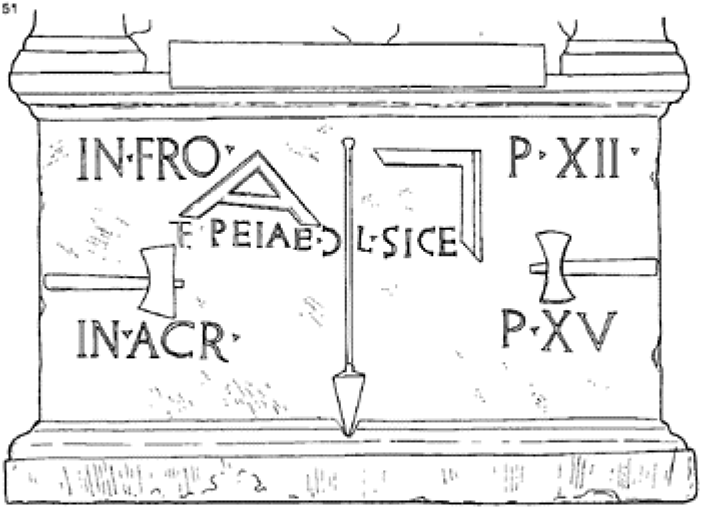
more easily attack the surfaces to be dressed without having to take up difficult positions. It is the instrument *par excellence* for working soft rock; it is still in standard use in Italy for the cutting of tufa, and excavations have uncovered some excellent examples from antiquity,[44] similar in every way to contemporary models (figs 53, 54, 55, 56). This observation can in fact be extended to the whole range of hand tools, whose forms were established during the Roman epoch and have remained the same into the twentieth century.

50



50 Funerary relief of a stone-mason, with the representation of a square, a stone-mason’s hammer (or kivel) and a scabbling hammer. (Musée de Berry, Bourges; JPA.)

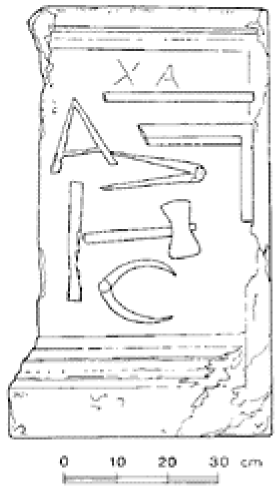
51



51 The base of a funerary monument on which are shown, from left to right: a mallet; a levelling square; a plumb line; a square; and a double-bladed

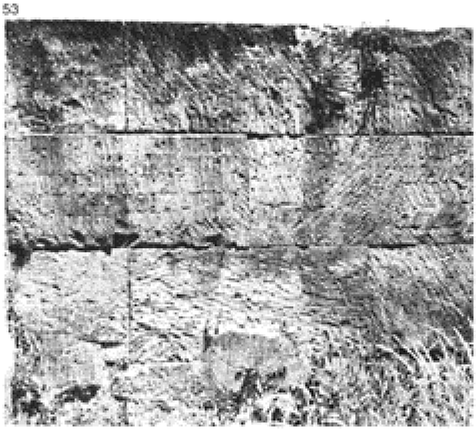
stone-hammer. (Museo della Civiltà Romana, room LII; JPA.)

52



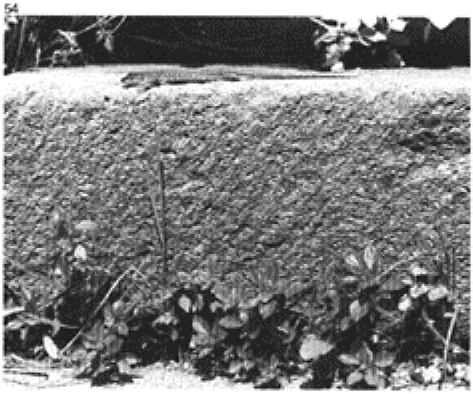
52 Stone-mason’s cippus showing: a foot without graduations (29.6cm long); a levelling square; a square; a compass; a maul or a bladed stone-hammer and calipers. (Capitoline Museum; JPA.)

53



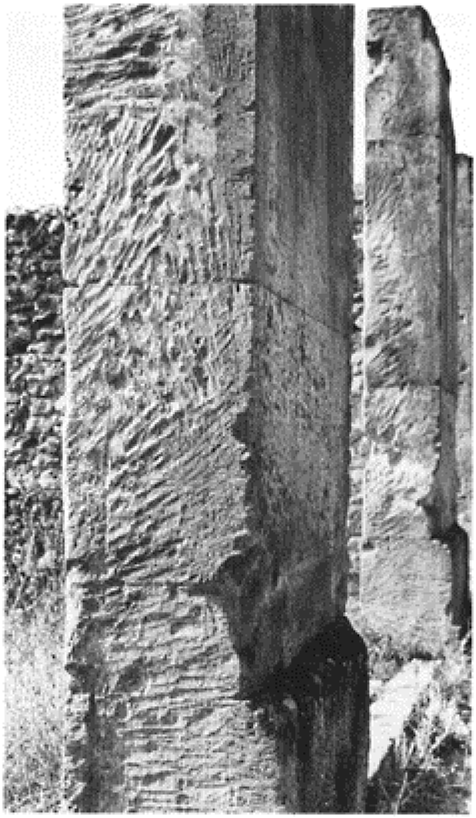
53 Different treatments of facings dressed with a stonehammer. Pompeii,

House of the Large Fountain (VI, 8, 22).



54 Marks of a bladed stone-hammer on a facing of lava. On hard rock the tool strikes the surface at an angle of almost 90 degrees, leaving shallow furrows. Herculaneum, *cardo* III.

55



55 The dressing of the facing of a pier made of tufa using a bladed stone-hammer; the marks carrying on across the joints indicate that the work was done after the blocks were put in position. Note that on this soft stone, the tool strikes obliquely and deeply. Pompeii VIII, 5, 26.

56

56 An ancient kivel or stone-mason's hammer and a modern one at Pompeii. The continuity in the form of this tool is remarkable.

57

57 A stone-mason rough dressing a facing stone with a punch or point.

In working a hard rock a smooth blade risks having its edge broken or dulled. A better percussion is obtained by using a toothed cutting edge (which can also of course be used on soft rocks), either with flat teeth, the bush-hammer, or with pointed teeth. It is significant that such details are not shown on the sculpted representations and that the cutting edges recovered up to now are not toothed, perhaps because this iron part, being finer and already cut out, has not survived. However, as the typical traces left by toothed tools are numerous and, since no toothed chisels have been found either, the existence of one type and/ or the other can be safely assumed.

It is also worth noting that some double blades had their two cutting edges perpendicular to the handle.[45] This form has practically disappeared in France but it can still be found in Greece—with smooth blades for cutting tufa and toothed blades for cutting hard stones.[46]

The second big family of stone-mason's tools are the tools of indirect percussion—tools whose cutting motion is caused by the blow of a percussor, possibly a wooden hammer, the mallet, made out of hard wood—boxwood or olive. This instrument is best used with chisels which also have wooden handles and are designed for soft stone.[47] When the percussor has a metal head its strength is greater and its precision less, and it is used for hard stones with chisels without a handle.

The first tool of indirect percussion, used for preliminary cutting or rustication, is the point or punch. Depending on whether the working was done vertically or obliquely, a punched marks joining up, and this cannot be dressing is obtained with percussion distinguished from dressing with a scabbling hammer; only the workman himself can make the identification, depend-ing on the tool he is using. Alternatively a broached dressing is achieved, with furrows that are parallel, vertical, oblique or concave, following the arc described by the arm movement (an effect that can also be achieved with the scabbling hammer) (figs 57, 58, 59, 60).

With the point or with the scabbling hammer the stone-masons (the *quadratarii* or *lapidarii*) set to work shaping a block, resting it on a wedge of stone or wood, so that it could be fixed at a convenient angle. In this way the block was chiselled to the line which marked out a rectangular face, the workmen checking its outline with a rule (to get a flat surface) and a square (to check right angles).

When the rough dressing has been completed with the scabbling hammer and the punch, the stone-mason refines his work with chisels, always starting with peripheral chiselling to define the lines of each face. The chisels either have a smooth edge—the straight chisel (the *scalprum*)—or are toothed—the claw chisel (the *gradine*) (fig. 61).

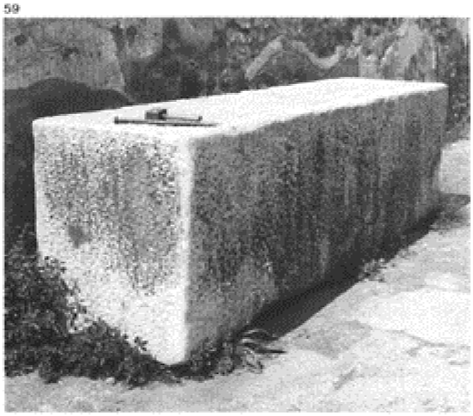
As the work carried out with the chisel is much more precise, analysis of the marks left makes it possible to distinguish whether the tool used was a hammer-blade or a chisel or else a bush-hammer or a *gradine*. Other evidence is provided by the width of the trace left, which is larger in the case of a cutting hammer or bush-hammer than in the case of chisels.

Finally, to the long series of chisels can be added the mallet-headed chisel, which has a cutting edge of greater thickness than its width; the driver, with a cutting edge forming almost a right angle and making it possible to cut the edges; and gouges with a concave cutting edge, used for carving curved mouldings.

58

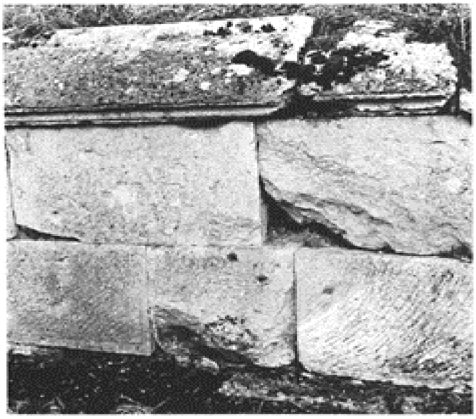
58 The stone-mason and sculptor Amabilis, working with a mallet and chisel. Funerary stele. (Musée de Bordeaux; JPA.)

59



59 A roughed-out block of white limestone, brought from the quarry with scabbled facings, intended for the reconstruction of the Forum at Pompeii after 62. Length: 3.07m; width: 0.73m; height: 1m; weight 5800kg.

60



60 Dressing on the blocks of a podium from the amphitheatre of Senlis. On the right-hand block the curve of the mason's strokes can be traced, in a regular movement.

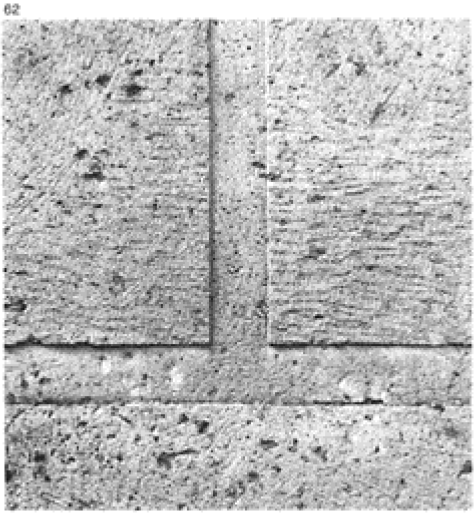
61

61 The carving of the anathyrosis band (with a break at the top), the rebating inside it and the bedding face, with the claw chisel. Site of the Temple of Venus, Pompeii.

The finishing of the facing of the blocks and the cutting of drafted margins and the anathyrosis rebating and, above all, any carvings, are done with the claw chisels, cutting very precisely. Sometimes the surface is polished, or burnished, by rubbing the stone, sprinkled with water, with a hard, close-grained rock, such as sandstone or volcanic rock (fig. 62). A polisher has been recovered on a working site in Pompeii consisting of a semi-spherical cupel of bronze, 6cm in diameter, with a gripping ring and containing a pumice stone.[48]

At cutting sites like quarries, in abandoned deposits such as the one at Ostia, or better still on the building sites at Pompeii, the different stages from the squared block to the finished piece can sometimes be traced with a remarkable continuity, especially when an entire series is found. Thus, in the Central Baths, begun at Pompeii after the earthquake of 62, the workmen were working on the one hand on the masonry of the walls and had got up to the level of the spring of the vaults, and on the other on the cutting of blocks intended for the floor paving and the orders of the portico. A series of four Doric capitals here illustrates perfectly the progress of the cutting;, starting with a block of stone which has approximately the shape of a truncated pyramid, the next step is the beginning of a roughed-out form in which the capital is already recognizable, the acanthus leaves appear on a third block while the fourth is complete (figs 63, 64, 65). At each of these stages it can be seen that the stone-mason changed tools, starting with a point and finishing with fine points and narrow chisels, taking care each time to finish the block in a perfectly homogeneous manner, an observation that can be made on the Corinthian capitals of one of the temples of Palmyra, on which the fineness of the dressing of the intermediate stages

62



62 Rustication in part carried out with a stone-hammer, in part with a claw chisel, with the joints polished or

ground. Pompeii, tomb 17, Nucerian Gate.

63

63 Capital from the Central Baths at Pompeii, in the original state, roughly dressed with a scabbling hammer and a point.

64

64 At this intermediate stage, the preparation is done with a claw chisel,

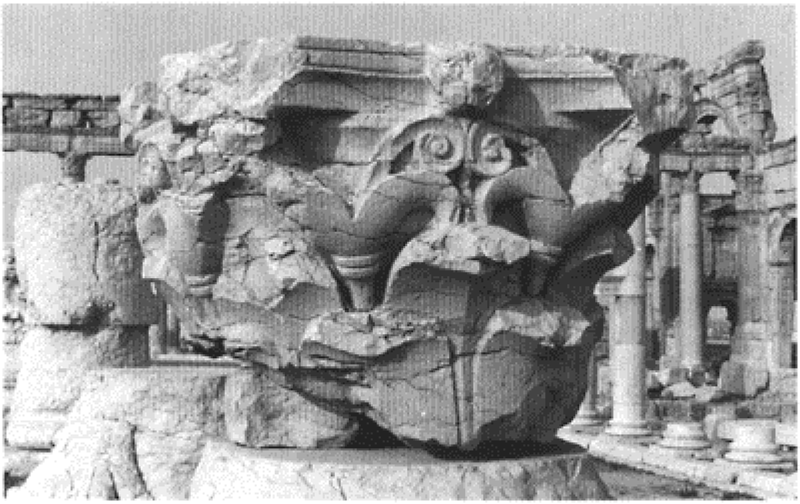
and the marginal drafts with a straight chisel.

65

65 The finished and polished capital.

equals that of the finished state (figs 66, 67).

66



66 Unfinished Corinthian capital, from the sanctuary to the south of the Grand

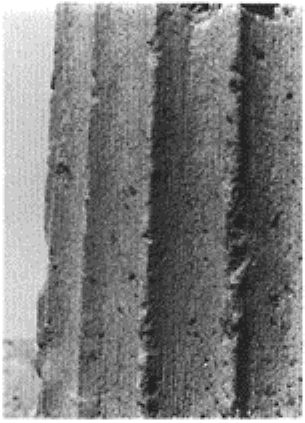
Colonnade at Palmyra. Note the extreme care of the finishing of the worked shapes.

67

67 A finished capital from the same series, damaged by its fall.

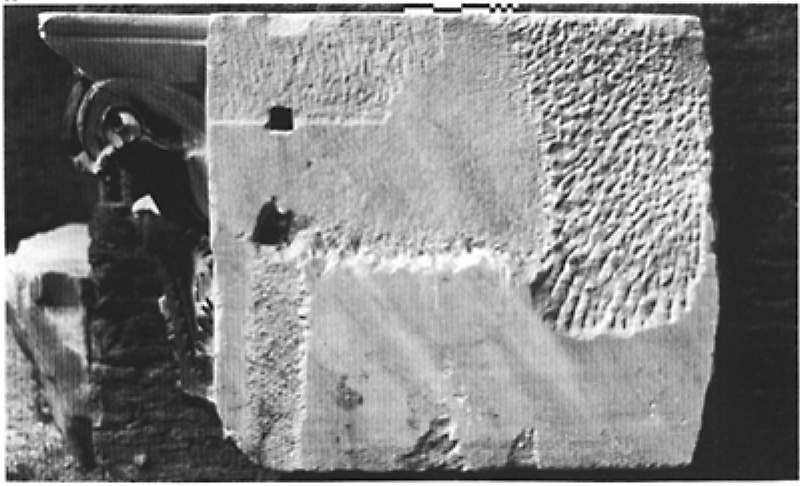
It was not rare for blocks to be assembled on the monument without being given their final dressing, with only the marginal drafts and the surfaces of the joints finished. Likewise, the elements of the mouldings were put in place and the decoration carried out at the same time as the final dressing, sometimes long after the end of the construction work. In certain cases this final dressing was only partially realized and the sculptures were unfinished, as can be seen on the gigantic Temple of Apollo at

68



68 Marks of the toothed chisel at the bottom of the fluting left by a continuous scraping with the tool, without the use of a percussor. Temple of Apollo, Pompeii.

69

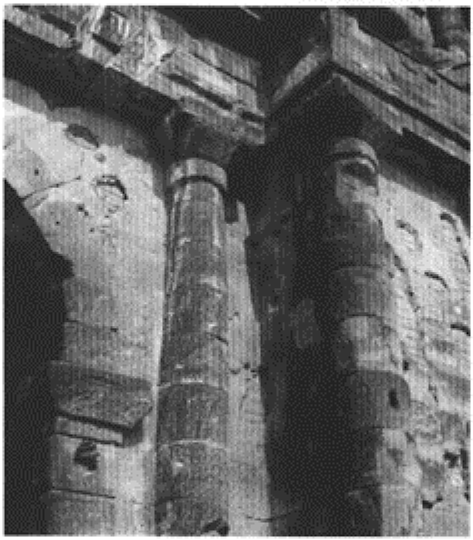


69 A block of marble, reused by apprentices for practising dressings. On the right is a sheaf-like dressing, which was scabbled by the workman face-on *(top),* then broached at the end of the movement *(below),* and three

exercises with a claw chisel, the one in the middle also having been ground. The rest of the surface is polished. Capital of a pilaster, National Musuem, Rome.

70 Unfinished column from the Temple of Euromos (Caria). The fluting was prepared by an axial groove indicating the depth to be reached.

71



71 Trier. The prepared blocks of Porta Nigra.

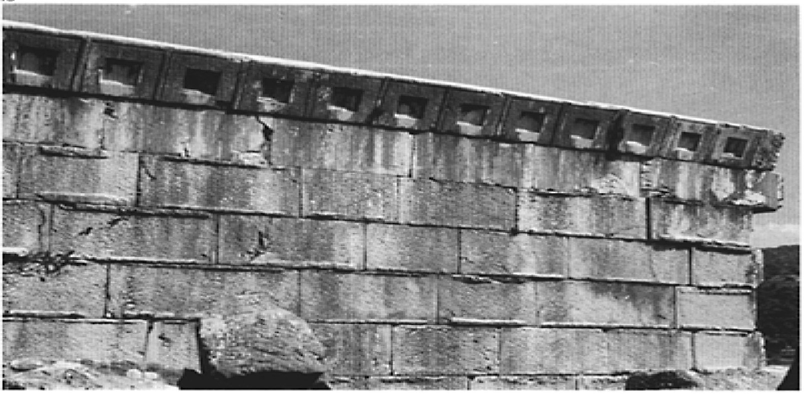
Didyma (near Miletus), or at its more modest neighbour, the Temple of Euromus, where the columns are smooth or partially fluted. The Porta Nigra at Trier and the tetrapylon supporting the pyramid of the Circus of Vienne likewise give the general

72

72 The unfinished tetrapylon of the pyramid of the Circus of Vienne.

impression of being complete, but the facings are only roughed out with a point or a scabbling hammer and

73



73 Vaulted building at Patara (Lycia) at the west of the port, the blocks of which have retained the protective flanges intended to preserve the edges during transport; final dressing was only carried out on the top course.

74

74 The sculptor’s tools were identical to the stone-mason’s, but the tool-kit contained a greater variety of chisels,

and sometimes, especially in the Later Empire, a brace and bit to drill the stone, such as the one seen on the stele of a sculptor of sarcophagi of the palaeo-Christian period. (Cemetery of Sant'Elena, via Labicana, Rome; JPA.)

the capitals only have the shape of a truncated cone that has just been sketched out (figs 68, 69, 70, 71, 72, 73).

Though turning is mainly associated with woodwork, it is useful to point out its use in the Roman period for shaping, in soft rock, column drums, capitals, Dorics and bases. Unfortunately, although the marks left by this method are clearly visible, no archaeological discovery in the form of either a machine or a representation has been made which would make a reconstruction of the tool possible. It is possible to imagine that the block was first roughed out with the usual tools, then placed in a frame where it was rotated so that it could be worked with a chisel.

To accelerate and simplify the treatment of the mouldings, the sculptor extended the use of the drill, used for small holes, to the preparation of the majority of motifs by stippling. The instrument may be of considerable size and become a rock-drill with a motor belt, necessitating its operation by two

75

75 Marks painted by the quarrymen to distinguish the destination of the stones. Lava quarry of Terzigno. The practice of marking stones to indicate their destination was already standard in ancient quarries.

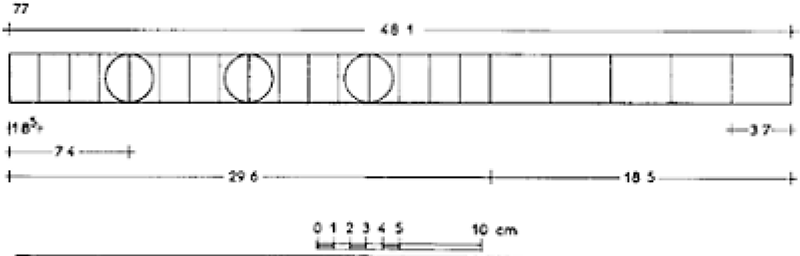
76

76 In the Republican period, the stone-masons, following a Greek custom, placed their mark on the blocks. Walls of Bolsena, third century BC. This custom was to reappear occasionally in the Imperial period, notably in North Africa.

workmen. A funerary relief from the via Labicana illustrates the working of such a machine (fig. 74).

Finally, it is worth noting that symbols on blocks could have been made by quarrymen, generally to indicate the lots by their order, but can also be the work of the stone-masons. This custom of masons' marks was very widespread in Hellenized regions but disappears at the end of the Republican period and makes its reappearance in the imperial era only

77



77 Graduated rule from the funerary stele of a naval carpenter. Ostia, *Cardo Maximus*.

sporadically, notably on certain monuments in North Africa (figs 75, 76).

c Measurements and checks

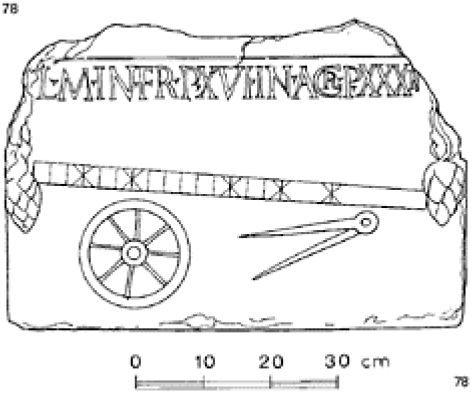
In the course of the different stages of roughing out, preparation and finishing, the stone-cutter periodically used different instruments not actually for working on the material but to ensure its correct form by measurements and checks.

The graduated rule *(regula)* was in constant use as it determined right from the start the outline of the edges of the block, in relation to its height, if it was being incorporated into regular courses, and to its width if it was a bonding stone or parpen.[49] The Roman rule was in fact a graduated foot which could be made of wood with metal ends but was more usually made of bronze. The National Museum of Naples has several examples of these made up of two articulated arms, each of half a foot, maintained in alignment by a locking device. Bone, because of its hardness, could also be used for making rules and one of this type has been found near the Theatre in Ostia with scored division markings (figs 77, 78, 79, 80).[50]

The length of the Roman foot has been the subject of numerous studies,[51] based both on the graduated rules found and on measurement studies carried out on standing structives; the values of the foot and its multiples and multiples of multiples given here were in general use in the Imperial period:

finger—*digitus*	$\frac{1}{16}$ foot	=	1.848cm
hand—*palmus*	$\frac{1}{4}$ foot	=	7.392cm
foot—*pes*	1 foot	=	29.57cm
palm—foot—*palmipes*	$1\frac{1}{4}$ feet	=	36.96cm
cubit—*cubitus*	$1\frac{1}{2}$ feet	=	44.355cm
pace—*gradus*	$2\frac{1}{2}$ feet	=	73.925cm
double pace—*passus*	5 feet	=	1.478m
furrow[52]—*actus*	120 feet	=	35.48m
mile—*mille passus*	5000 feet	=	1478.50m

The standard size of the foot is known from the bronze foot rules as they were made with the greatest precision; but funerary stelae can also be referred to. The Museo della Civiltà Roma in Rome[53] has assembled a series of stelae of arti-



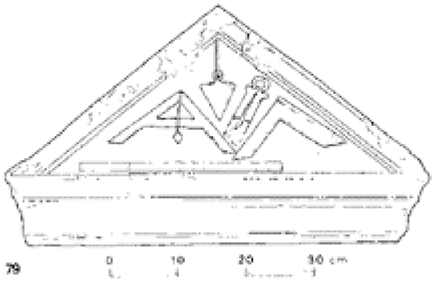
78 Stele of a carter, showing a rule of 2 feet (1.59cm), divided into half-feet, palms ($\frac{1}{4}$ ft) and $\frac{1}{16}$ft. (Museo della Civiltà Romana, room LII, stele 58; JPA.)

sans on which are depicted graduated rules, some of them almost as long as 29.57cm. Thus of 10 pictorial representations five have rules shown at a size similar to that of the bronze originals– 29cm, 29.6cm, and three at 29.8cm; two are a double foot (58.5cm); and the last three appear to portray an arbitrary length (23cm, 40cm, 50.4cm). On the fine marble stele of a naval carpenter found on the *cardo maximus* at Ostia and still in place, the rule and its graduations are shown with a remarkable accuracy. It is a graduated piece divided unequally by a bold line into two lengths, 29.6cm and 18.5cm respectively, or 1 foot and 10 fingers. The foot is divided into four hands of 7.4cm, each one subdivided into four fingers of 1.85cm; for their part the 10 fingers comprise five divisions of 3.7cm or five double fingers, totalling 48.1cm which, when compared with the equivalent length of 48.05cm measured on bronze feet, gives a perfectly acceptable error of 5mm (approximately $\frac{1}{200}$).

The squares *(normae)* that have survived, like almost all precision instruments, are made of bronze and are of various sizes. Some of them called shouldering squares have a stand along one of their arms allowing them to be left in position. Others with articulated arms, are adjustable squares or bevelsquares allowing any angle to be set, be it dressing voussoirs, polygonal pieces or mouldings (figs 79, 80, 84).

Others again, frequently represented on the reliefs of artisans, had quite a different use: they were used to check

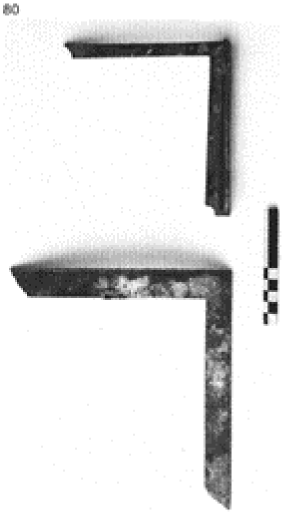
79



79

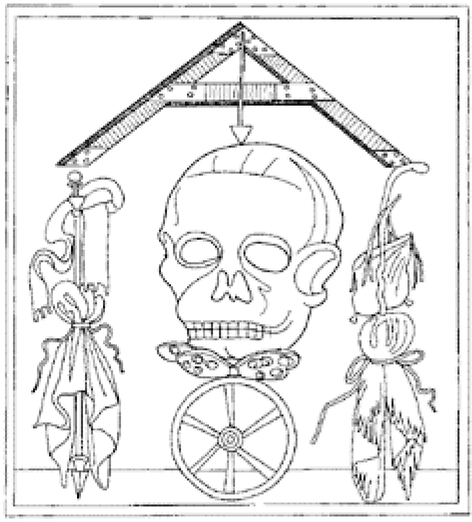
79 Relief of a mason showing a levelling square, a plumb line, an articulated square, a shouldering square and a rule of 1 foot (I.29.8cm). Tomb of a freeman of the *gens Aebutia*. (Capitoline Museum; JPA.)

80



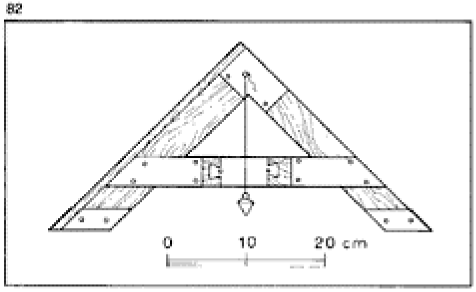
80 Two bronze squares found in Pompeii. The top one is a shouldering square. (National Museum, Naples.)

81



81 Levelling square with wooden arms and bronze attachments. Emblema, from a mosaic in a house in Pompeii (I, V, 2). (Museum of Naples; JPA)

82



82 Reconstruction of a levelling square from the Jardins du Luxembourg; the width of the wood pieces is fixed by the small arbitrary. (JPA after J.Conneau, bronze plates but the length is *Une querre gallo-romaine, Bulletin archéologique du Vexin,* 1, pp. 79ff.)